High-Fidelity, Weather-Informed Modeling of Future Energy Systems

Prepared By:

Vibrant Clean Energy, LLC
Dr Christopher T M Clack

Prepared For:

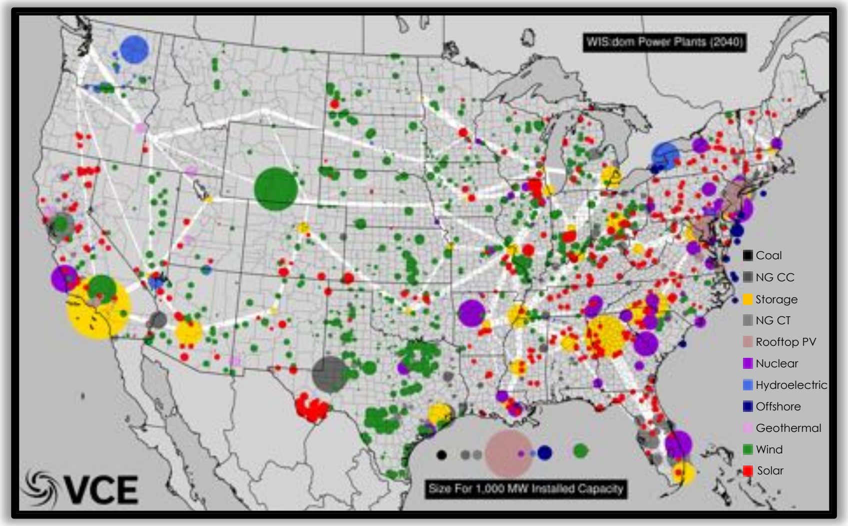
Colorado Public Utilities Commission
May 24th, 2018

Disclaimer:

info@vibrantcleanenergy.com

VCE

Who Are We: Vibrant Clean Energy



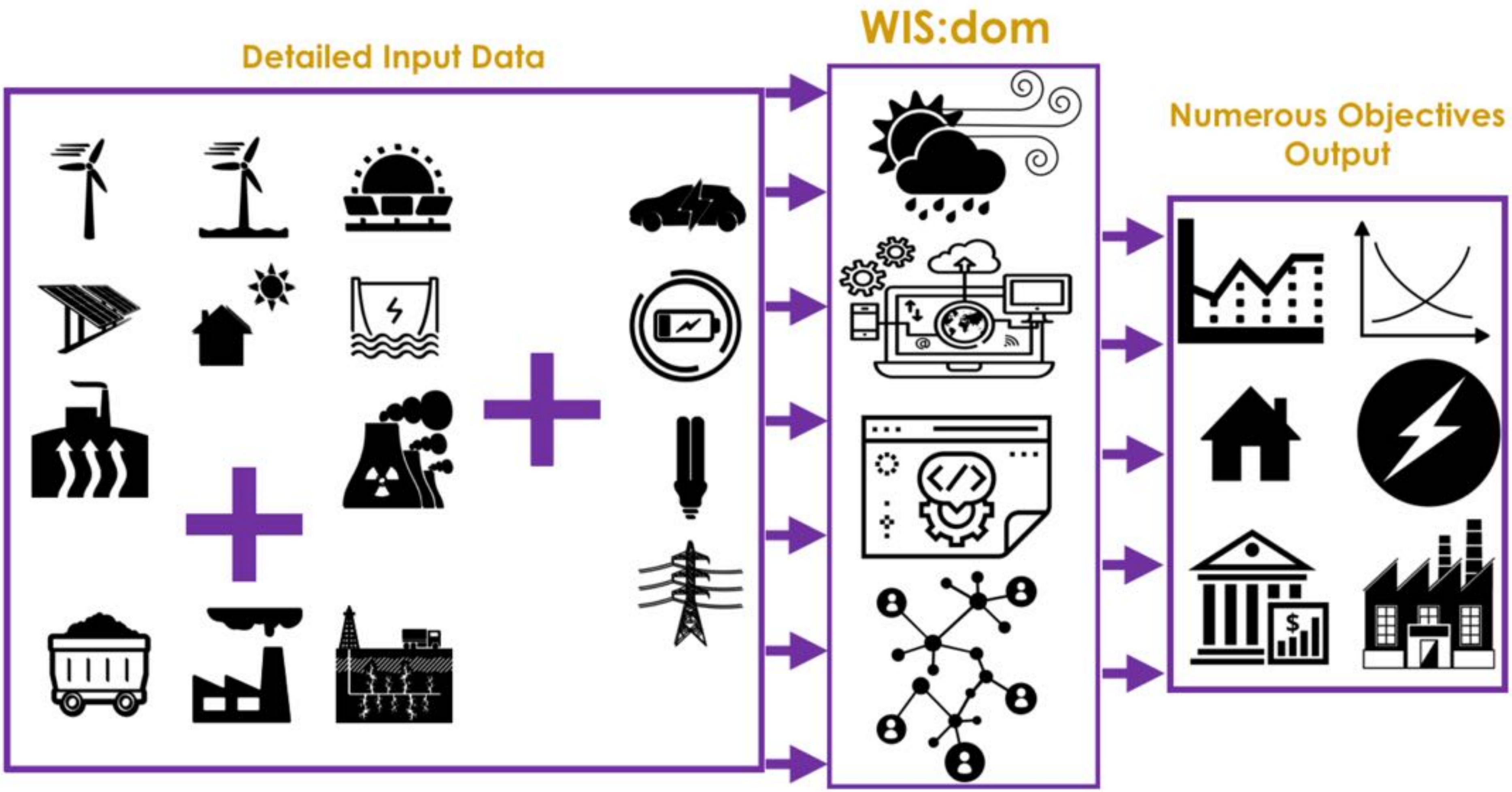
Purpose of Vibrant Clean Energy, LLC:

- Reduce the cost of electricity and help evolve economies to near zero emissions;
- Co-optimize transmission, generation, storage, and distributed resources;
- Increase the understanding of how Variable Generation impacts and alters the electricity grid and model it more accurately;
- Agnostically determine the least-cost portfolio of generation that will remove emissions from the economy;
- Determine the optimal mix of VG and other resources for efficient energy sectors;
- Help direct the transition of heating and transportation to electrification;
- License WIS:dom optimization model and/or perform studies using the model;
- Ensure profits for energy companies with a modernized grid;
- Assist clients unlock and understand the potential of high VRE scenarios, as well as zero emission pathways.

What Models Currently Do

- For production cost – typically short time periods & small geographic scope;
- For capacity expansion – typically coarse data, large region, but simplified / no dispatch;
- Typically many models do not consider demand side resources, transmission, storage, or other emerging technologies (EVs, heat pumps, water heaters, etc.);
- Disaggregation of components of the system leads to inefficient future projections and diminishes value of certain resources;
- Simpler modeling does not allow foresight beyond "knowns" for example, emergent behavior of market design, co-optimization of DERS, utility generation, transmission, and storage, reducing reliance on thermal generation for reserves, etc.
- Ignoring the changing environment, i.e. outside a specific BAA will lead to over investment and stranded assets / addition costs to rate payers, as the external regions will impact the internal dynamics of the BAA.

Pushing The Envelope: The WIS:dom Model



What Models Can & Should Do

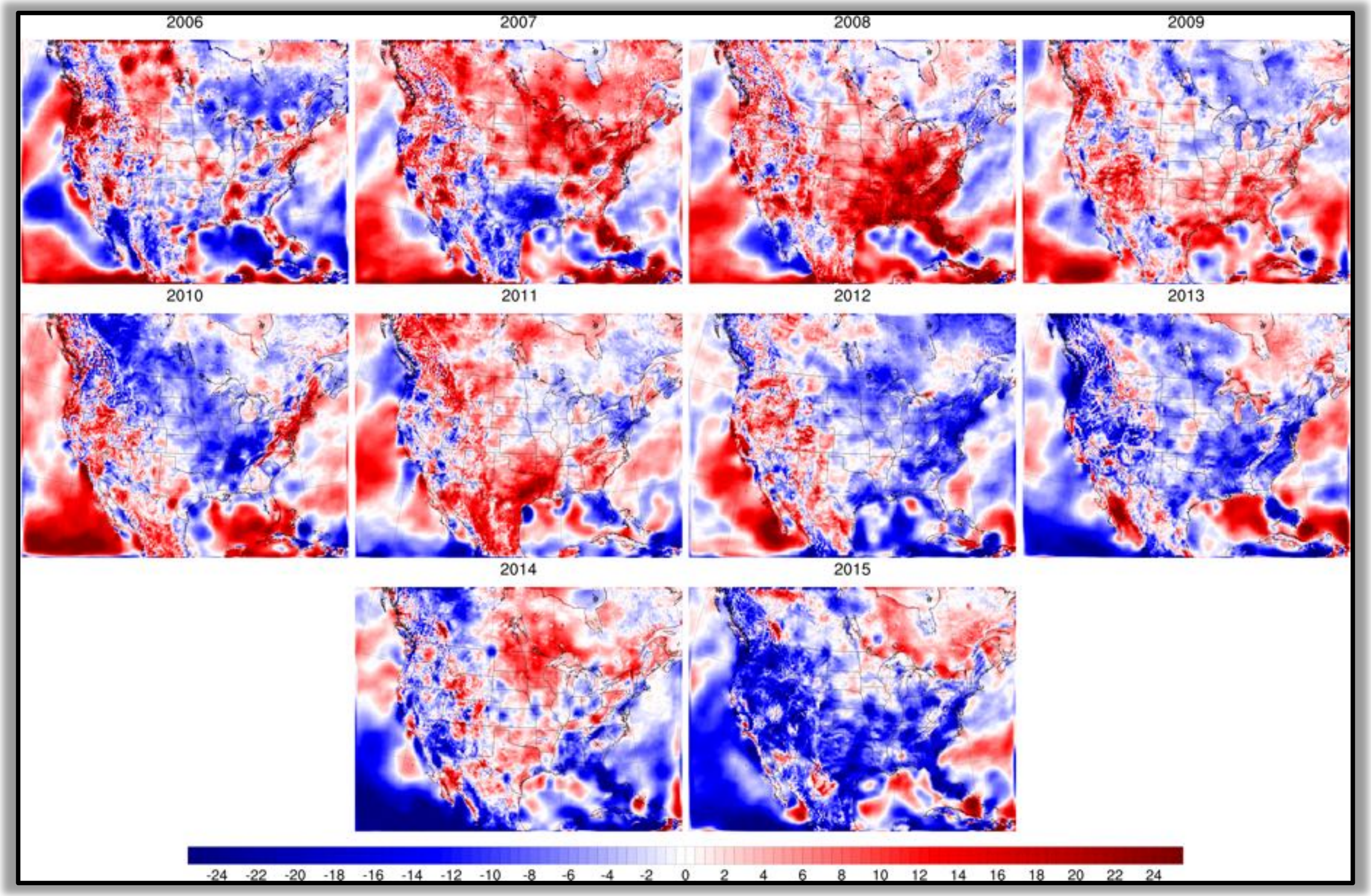
WIS:dom is the ***only*** (others should follow) combined capacity expansion and production cost model. It combines:

- ✓ Continental-scale (globally capable), spatially-determined co-optimization of transmission, generation and storage expansion while simultaneously determining the dispatch of these sub systems at 13-km or 3-km, hourly or 5-minutely resolution;
- ✓ Dispatch includes:
  - ➢ Individual unit commitments, start-up, shutdown profiles, and ramp constraints;
  - ➢ Transmission power flow, planning reserves, and operating reserves;
  - ➢ Weather forecasting and physics of weather engines;
  - ➢ Detailed hydro modeling;
  - ➢ High granularity for weather-dependent generation;
  - ➢ Existing generator and transmission asset attributes such as heat rates, line losses, power factor, variable costs, fixed costs, capital costs, fuel costs, etc.;
- ✓ Large spatial and temporal horizons;
- ✓ Policy and regulatory drivers such as PTC, ITC, RPS, etc.;
- ✓ Detailed investment periods (2-, 5-, or 10- year) out past 2050;
- ✓ **100 - 10,000x increased resolution** compared with nearest competitor for VRE, load, and conventional generator descriptions.
- ✓ ***Designed, operated and supported by small team.***

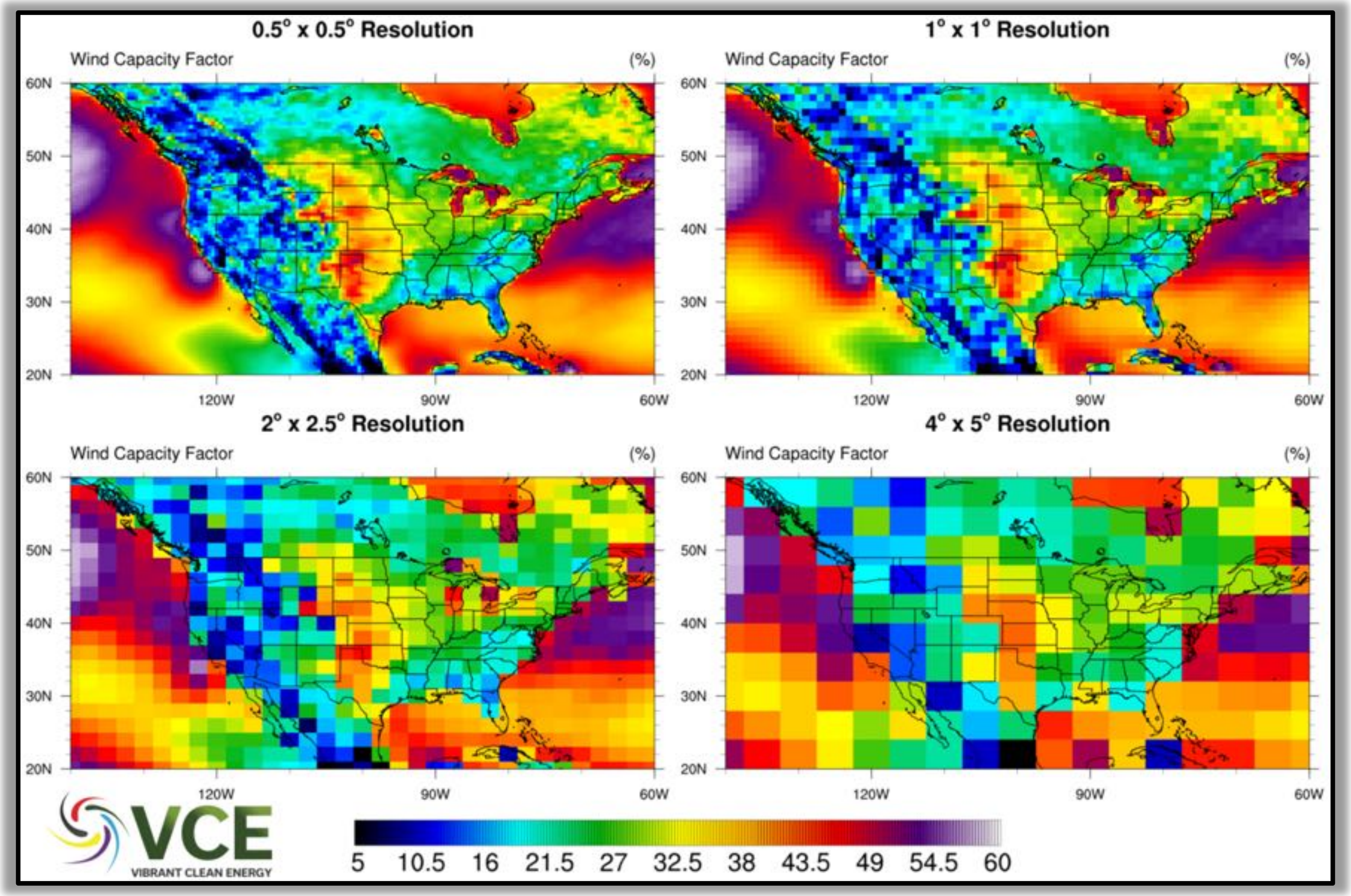
VCE VIBRANT CLEAN ENERGY

What Do We Think Models Should Consider?

Multi-Year Data Considerations

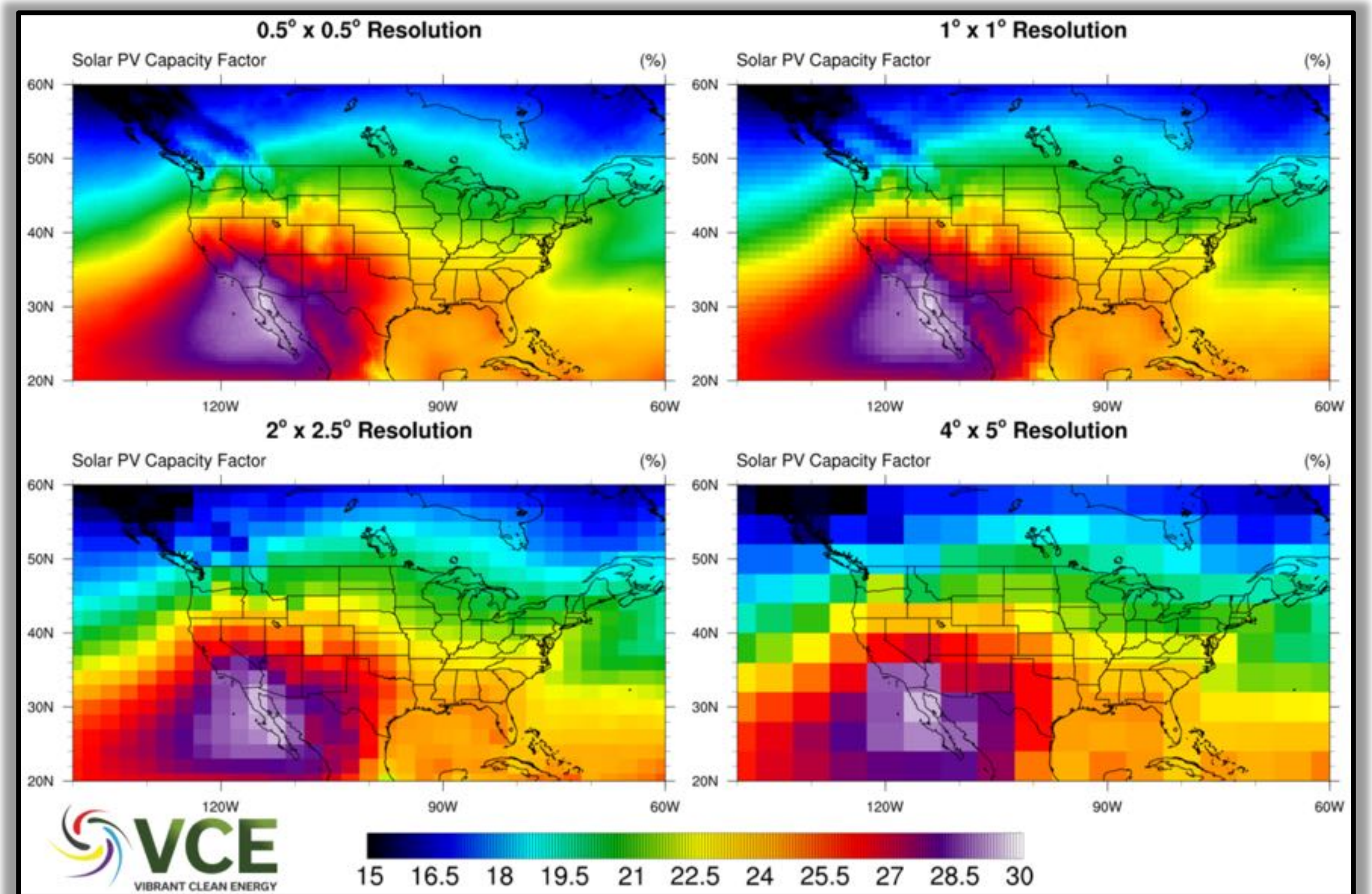


Resolution Considerations

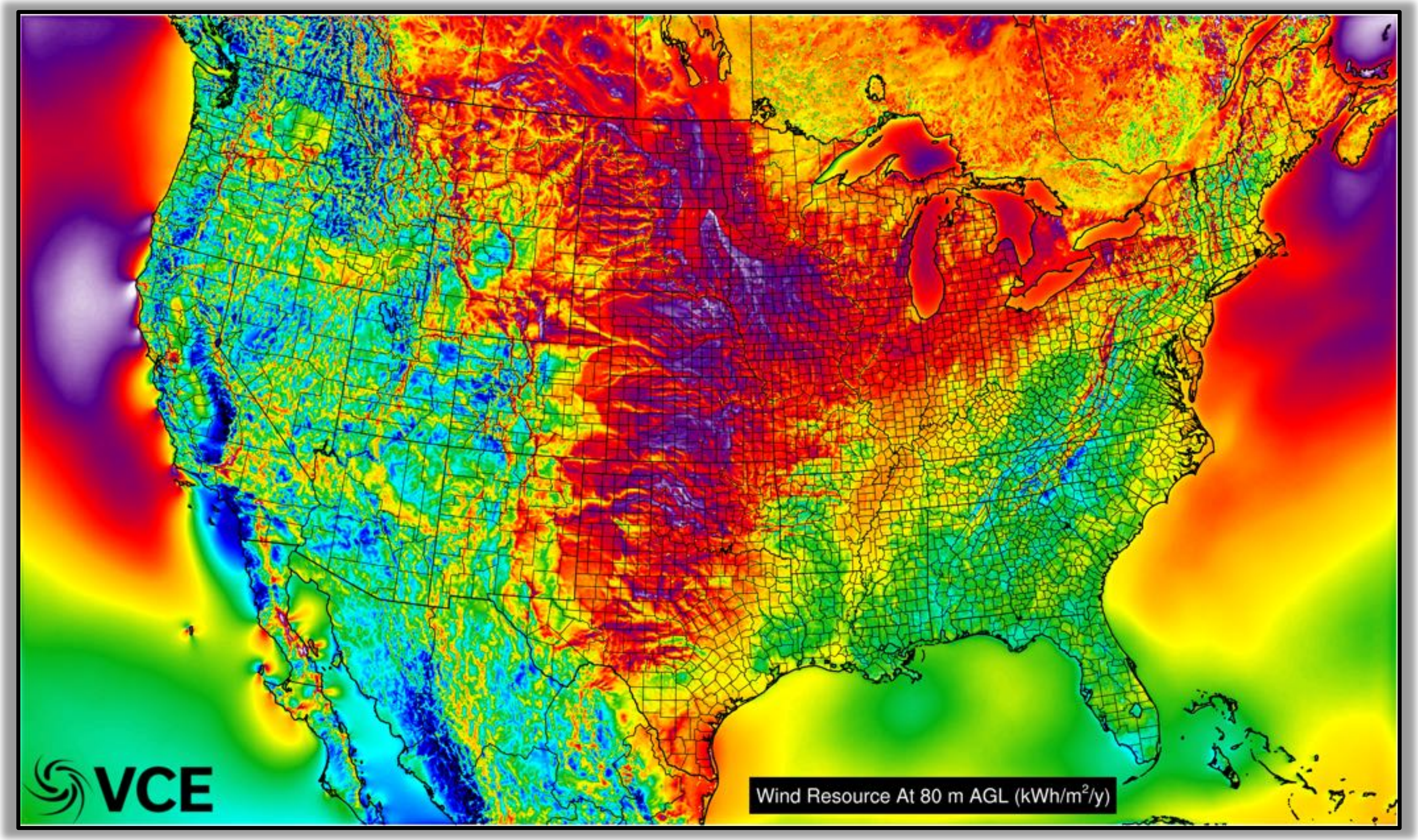


VCE
VIBRANT CLEAN ENERGY

Resolution Considerations

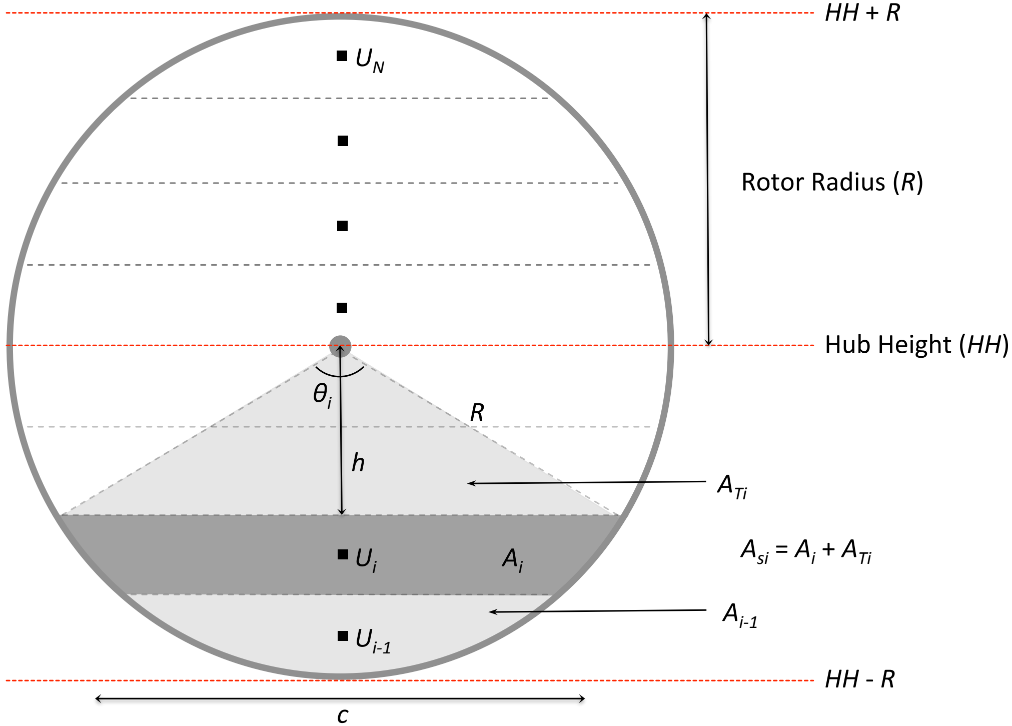


Wind Resource



Creating VRE Resources

General Process: Wind



$$U_\eta = \sqrt{u_\eta^2 + v_\eta^2}$$

$$U_i = \frac{u_i \cdot u_H + v_i \cdot v_H}{U_H}$$

$$A_i = A_{Si} - A_{Ti} - \sum_{j=0}^{i-1} A_j, \quad i \geq 1$$

$$A_{Si} = \frac{\theta_i}{2\pi} \cdot \pi R^2 = \frac{\theta_i R^2}{2}$$

$$A_{Ti} = \frac{1}{2} \cdot c \cdot h = R \sin\left(\frac{\theta_i}{2}\right) R \cos\left(\frac{\theta_i}{2}\right) = \frac{R^2}{2} \sin \theta_i$$

$$\alpha_i = \frac{A_i}{A} = \frac{(\theta_i - \sin \theta_i)}{2\pi} - \frac{1}{A} \sum_{j=0}^{i-1} A_j, \quad i \geq 1$$

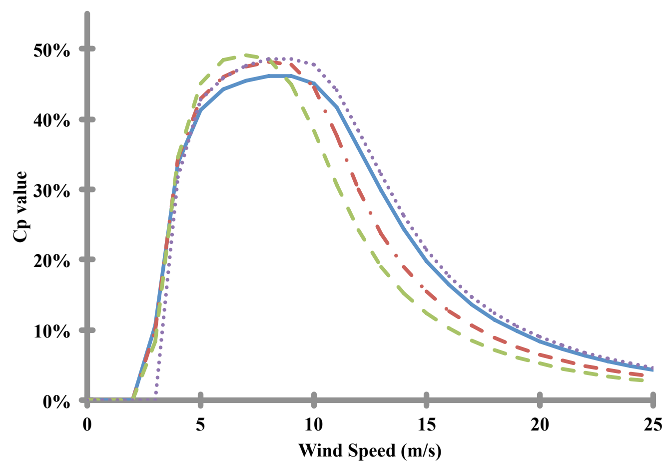
$$U_R = \sum_{i=1}^{N} \alpha_i \cdot U_i$$

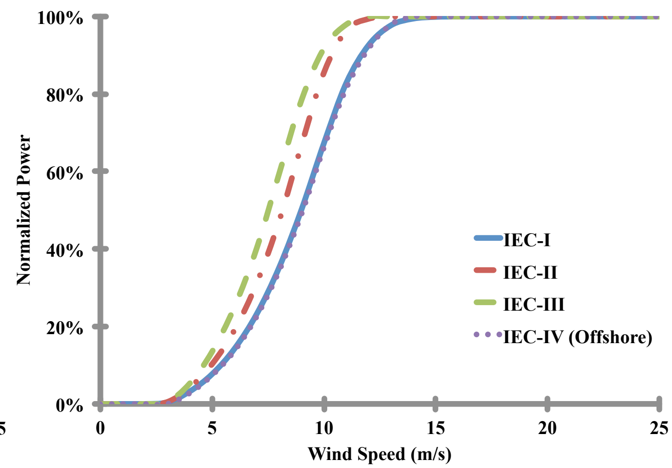
* We also perform the same technique to obtain the Rotor Equivalent Density, Temperature and Clouds

Creating VRE Resources

General Process: Wind

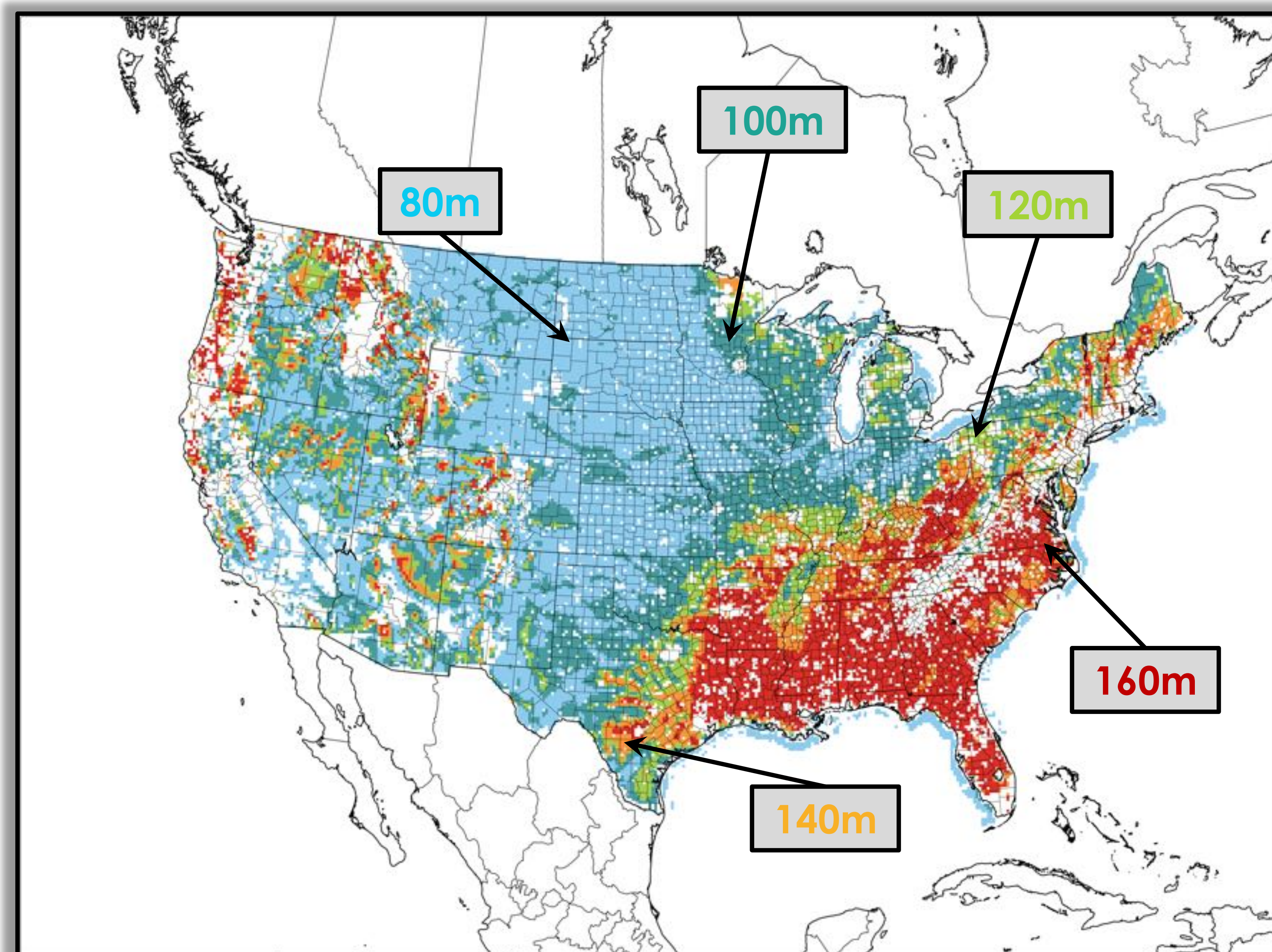
$$P_w = \frac{d[E_w(U(t))]}{dt} = \frac{d}{dt}\left[\frac{1}{2}\cdot A\cdot\rho(t)\cdot L(t)\cdot U^2(t)\right] = \frac{\rho A U^3}{2}\left[1+\left(\frac{\int U\,dt}{U}\right)\left(\frac{1}{\rho}\frac{d\rho}{dt}+\frac{2}{U}\frac{dU}{dt}\right)\right]$$



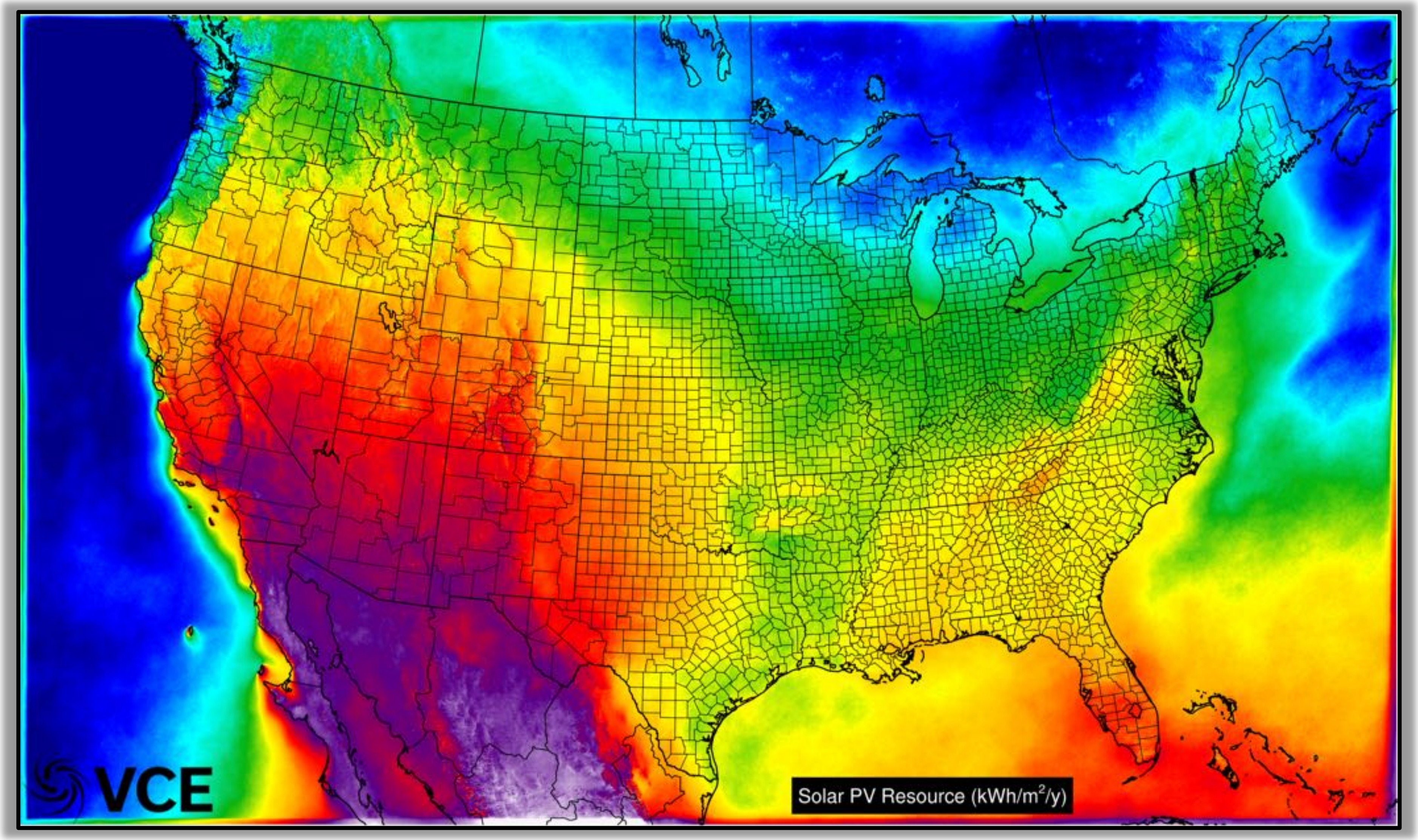


	Turbine	Rated Power (MW)	Cut-In Speed (m/s)	Max Output Speed (m/s)	Cut-Out Speed (m/s)	Rotor Diameter (m)
IEC-I	Siemens 3.0 MW	3.0	3.0	14.0	25.0	101.0
	Gamesa G80	2.0	4.0	17.0	25.0	80.0
	Nordex N90HS	2.5	4.0	14.0	25.0	90.0
	Vestas V90	3.0	4.0	14.0	25.0	90.0
IEC-II	Vestas V112	3.0	3.0	13.0	25.0	112.0
	Siemens 2.3 MW	2.3	3.0	13.0	25.0	93.0
	GE1.6 82.5	1.6	4.0	12.0	25.0	82.5
	GE2.5xl	2.5	3.0	14.0	25.0	100.0
IEC-III	Vestas V100	1.8	3.0	12.0	20.0	100.0
	GE1.6-100	1.6	3.0	12.0	25.0	100.0
	Repower 3.2M	3.2	3.0	12.0	22.0	114.0
IEC-IV	Siemens 3.6 MW	3.6	4.0	14.0	25.0	107.0
	GE4.1MW	4.1	4.0	14.0	25.0	113.0
	Repower 6M	6.15	3.5	14.0	30.0	126.0

Multiple "Flavors" of Technologies



Solar PV Resource

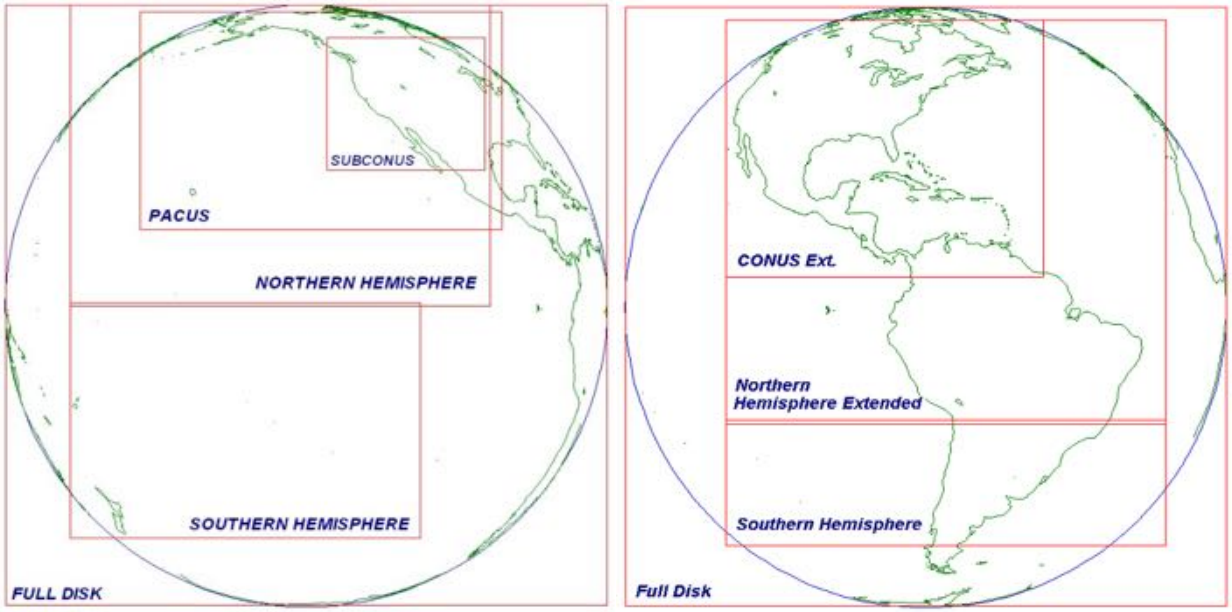


Creating VRE Resources

General Process: Solar

1. Obtain the ***3-km HRRR*** (High-Resolution Rapid Refresh) ***hourly*** data that includes 3-D volume of atmosphere over North America. Contains (1059 x 1799 x 51) data points for each variable.

2. Obtain the ***1- and 4-km GOES*** Satellite ***15-minute*** data for all of North America. The North America data is at a higher refresh rate that the full-disk scans. The reflectance values are for different wavelengths or "bands" – ***visible***, ***4-micron***, ***11-micron***, ***13-micron***, and ***water vapor***. VCE utilizes ***CONUS Ext***. and ***PACUS*** from the GOES satellites.



Creating VRE Resources

General Process: Solar

$$Y_{n\times p} = Z_{n\times(r+1)}\beta_{(r+1)\times p} + \epsilon_{n\times p},$$

$$E(\epsilon_{(i)}) = 0, \quad \text{Cov}(\epsilon_{(i)}, \epsilon_{(k)}) = \sigma_{ik}I, \quad i,k = 1,2,...,p.$$

- We have p(=3) irradiance fields to calculate and n(=631,645) observation of each field. The observations are taken from 15 high quality measurement sites (NOAA SURFRAD & SOLRAD)

- The regressors (β) are the satellite data (5 wavelengths), the HRRR weather variables (SW, LW, temperature, wind, elevation, etc.), the top of atmosphere irradiance, the zenith angle, the azimuth angle, and the declination angle.

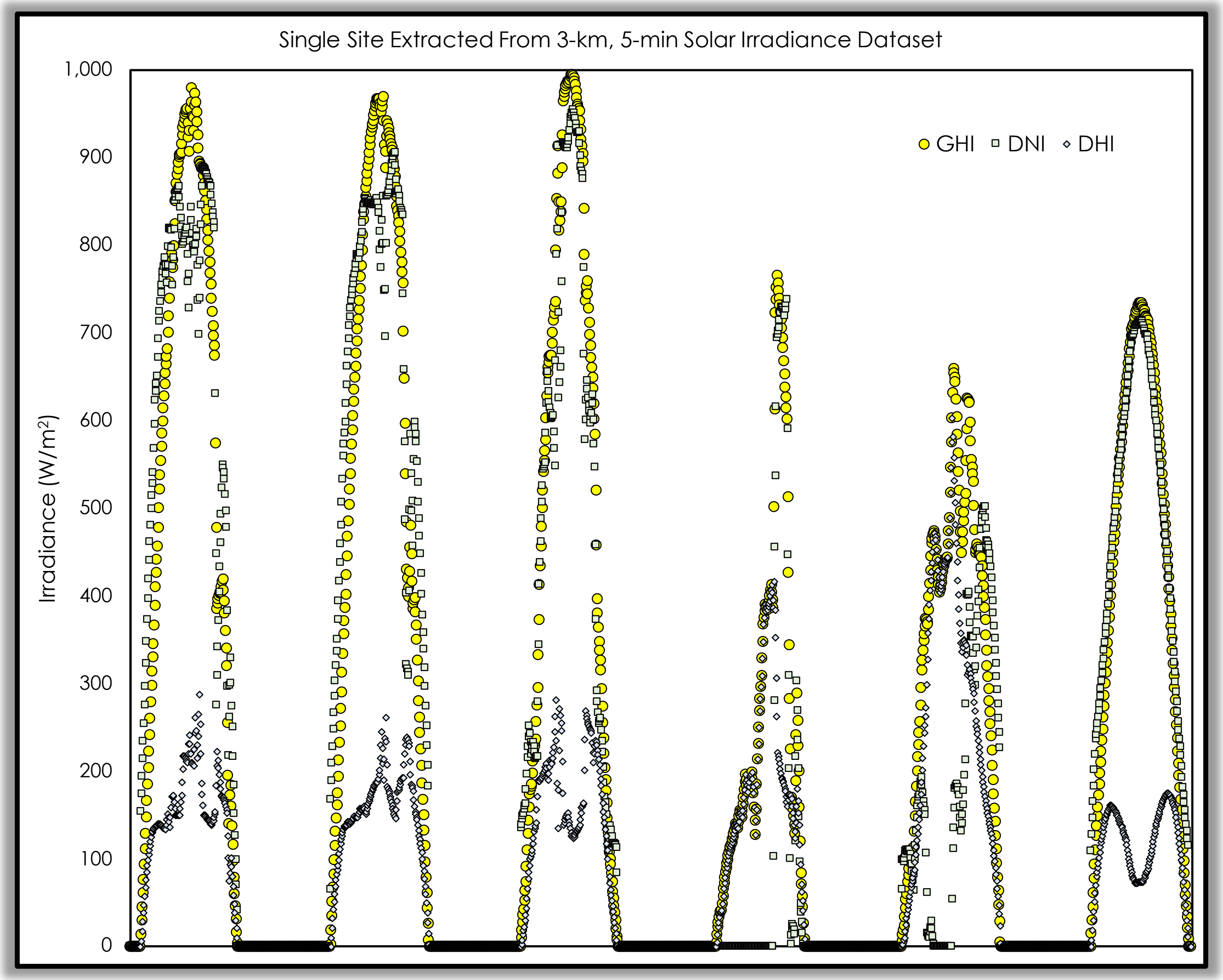
- The measurements are taken for each of the weather years, the closest 5-minute interval and aligned to the correct UTC time

- The data is quality controlled, and all night-time measurements were removed. The regression is trained at sites that are dispersed across the USA.

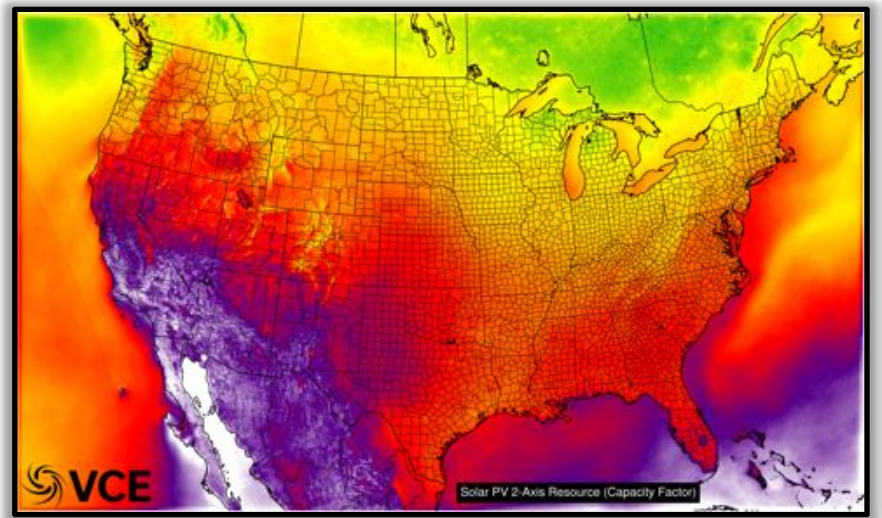
- Separate regressions are performed with and without satellite data, so that when no satellite is available an approximation is made.

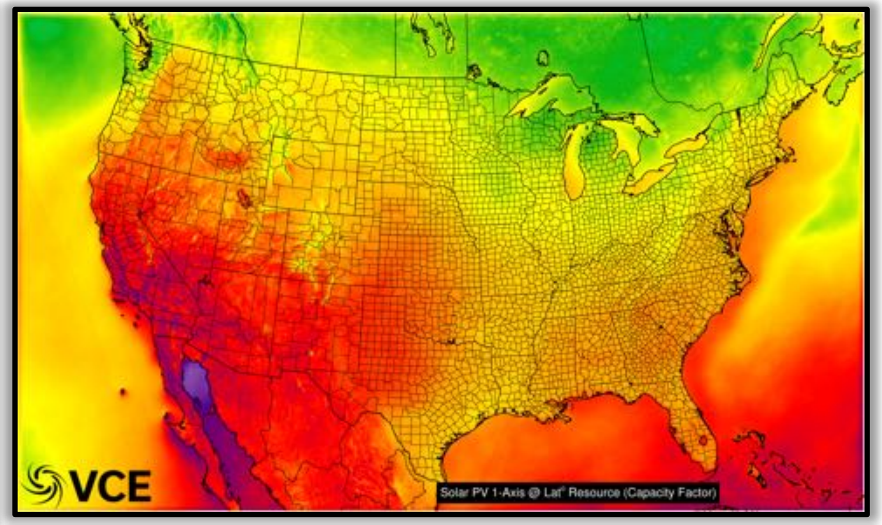
Creating VRE Resources

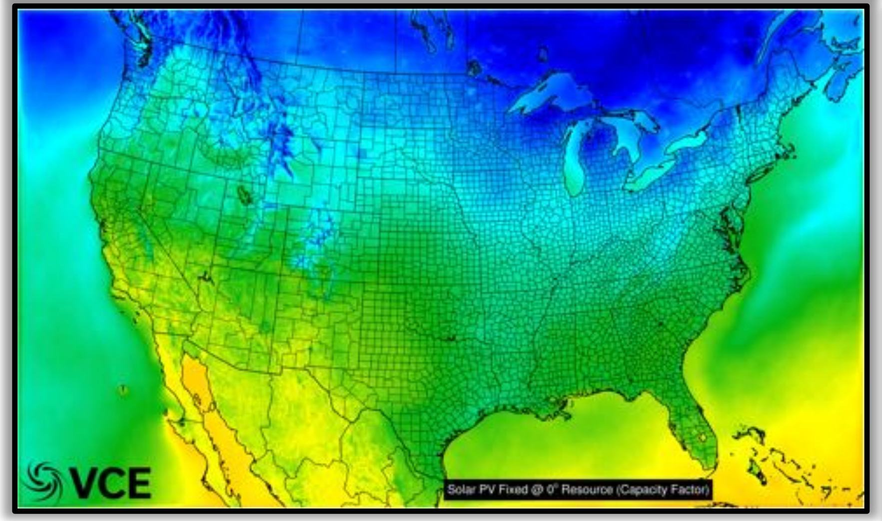
General Process: Solar

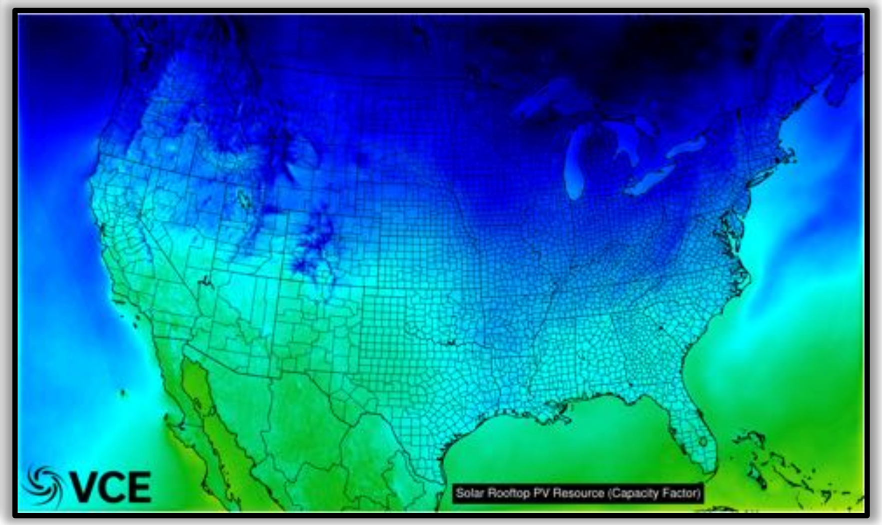


Multiple “Flavors” of Technologies

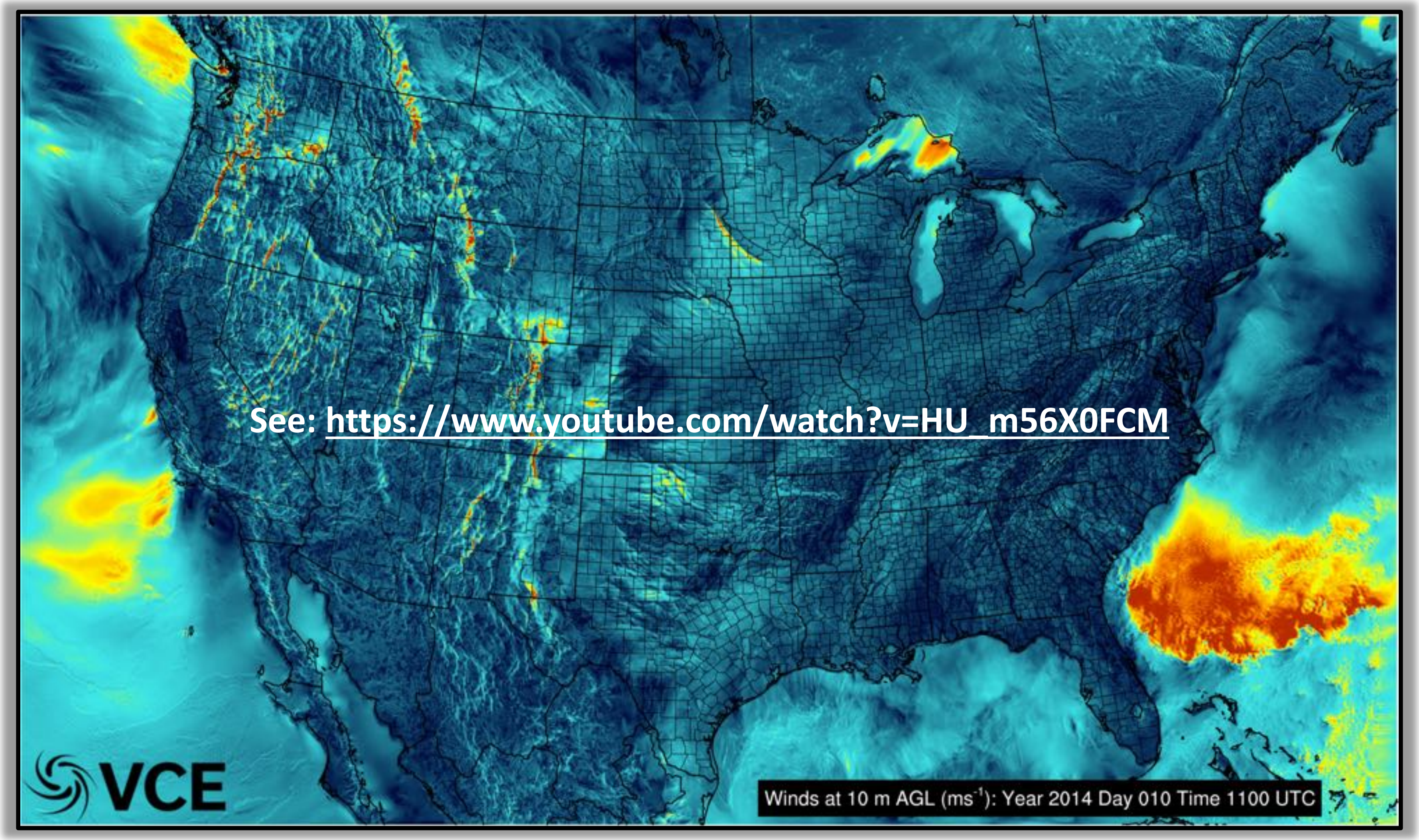








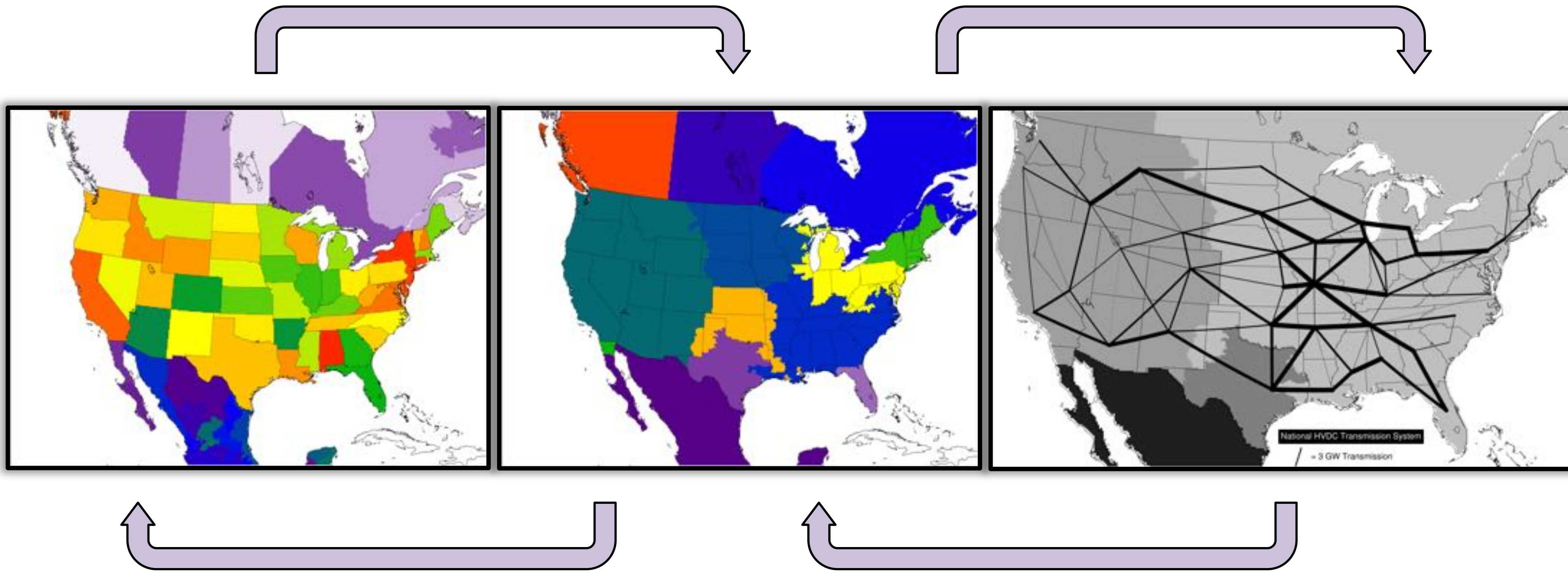
Wind Speed From 3-km, 5-min Dataset



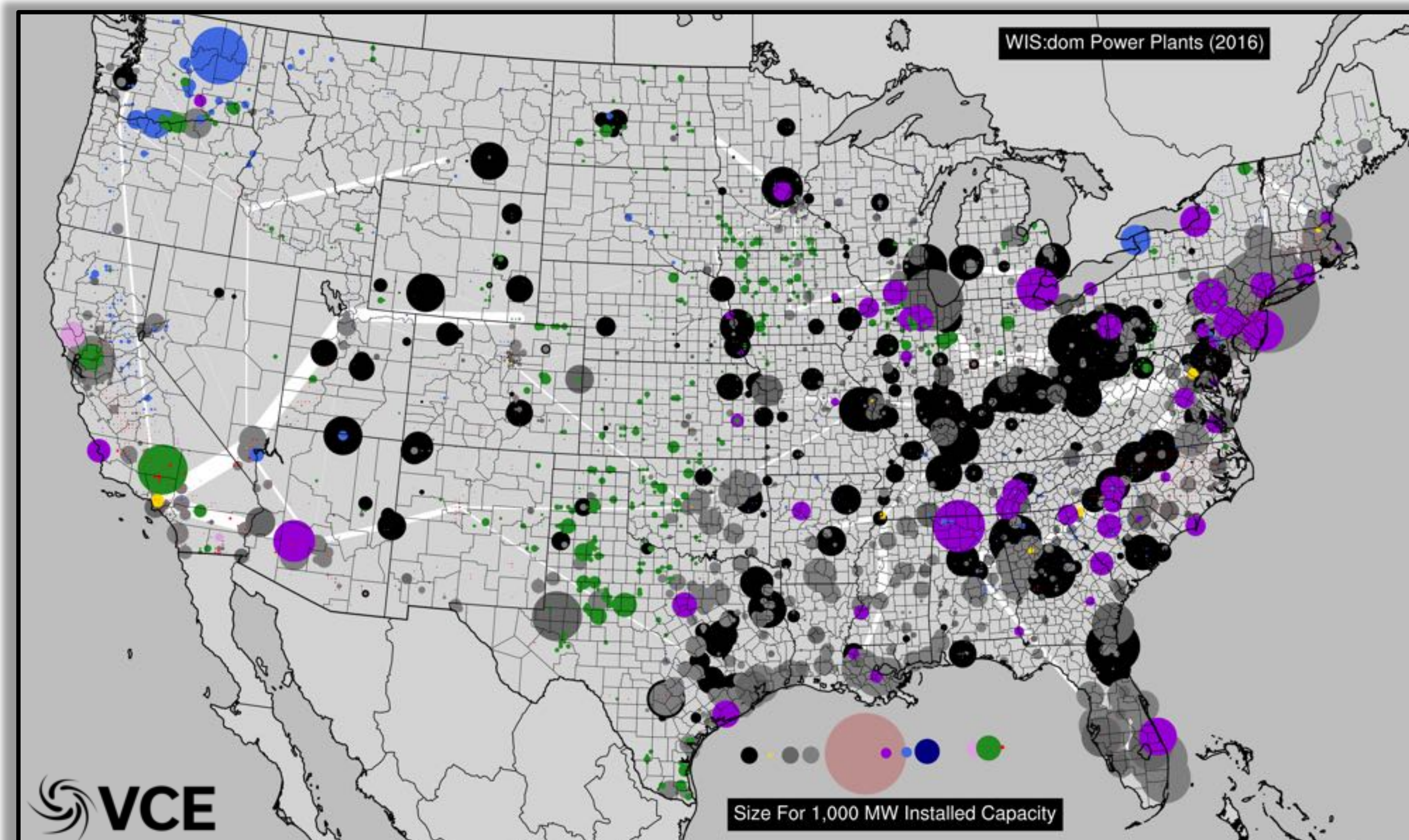
See: https://www.youtube.com/watch?v=HU_m56X0FCM

PV Power From 3-km, 5-min Dataset

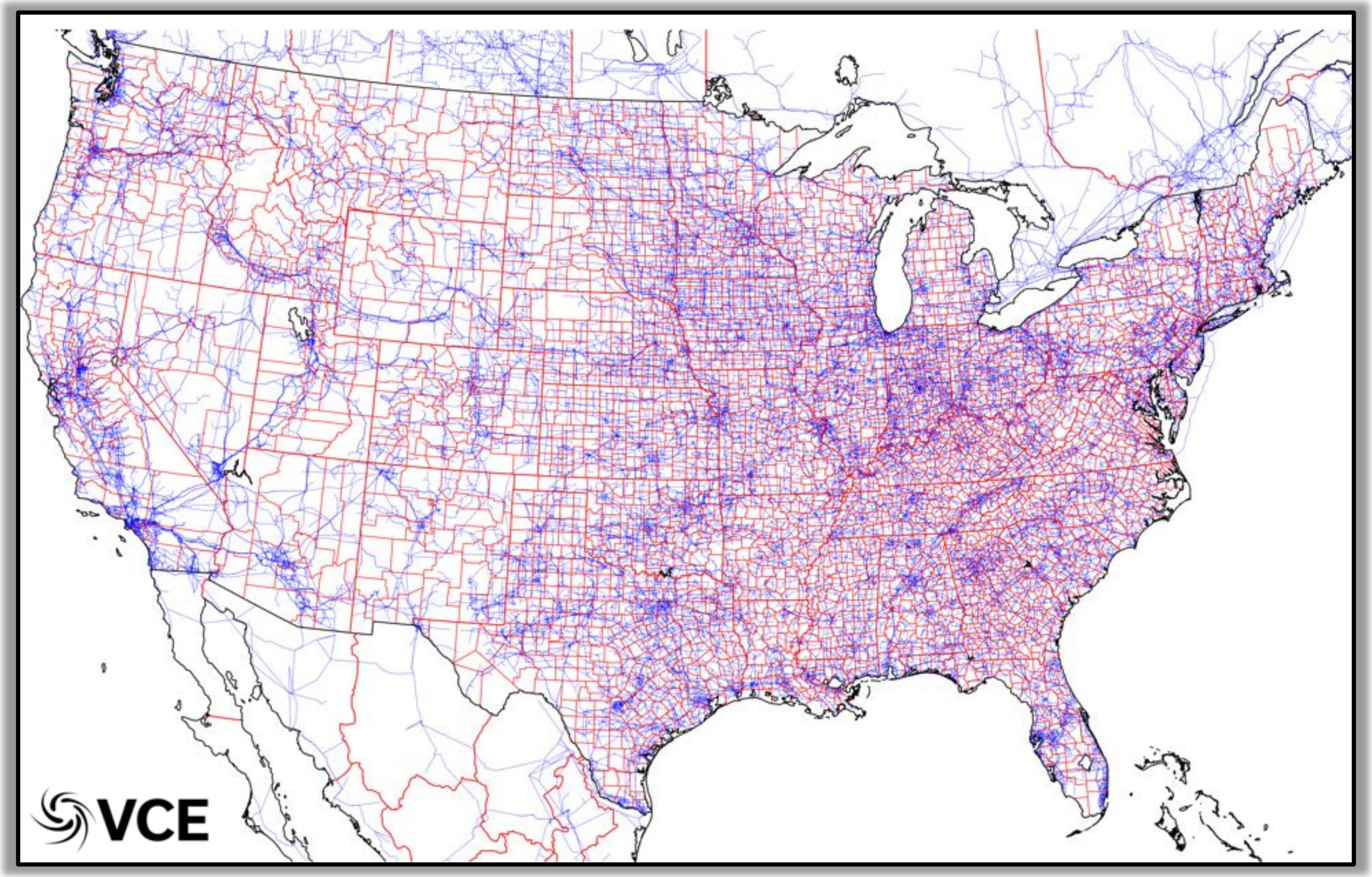
Consider: Various Scales Simultaneously To Produce Optimal Solutions That Incorporate Data Outside of Domain Of Interest



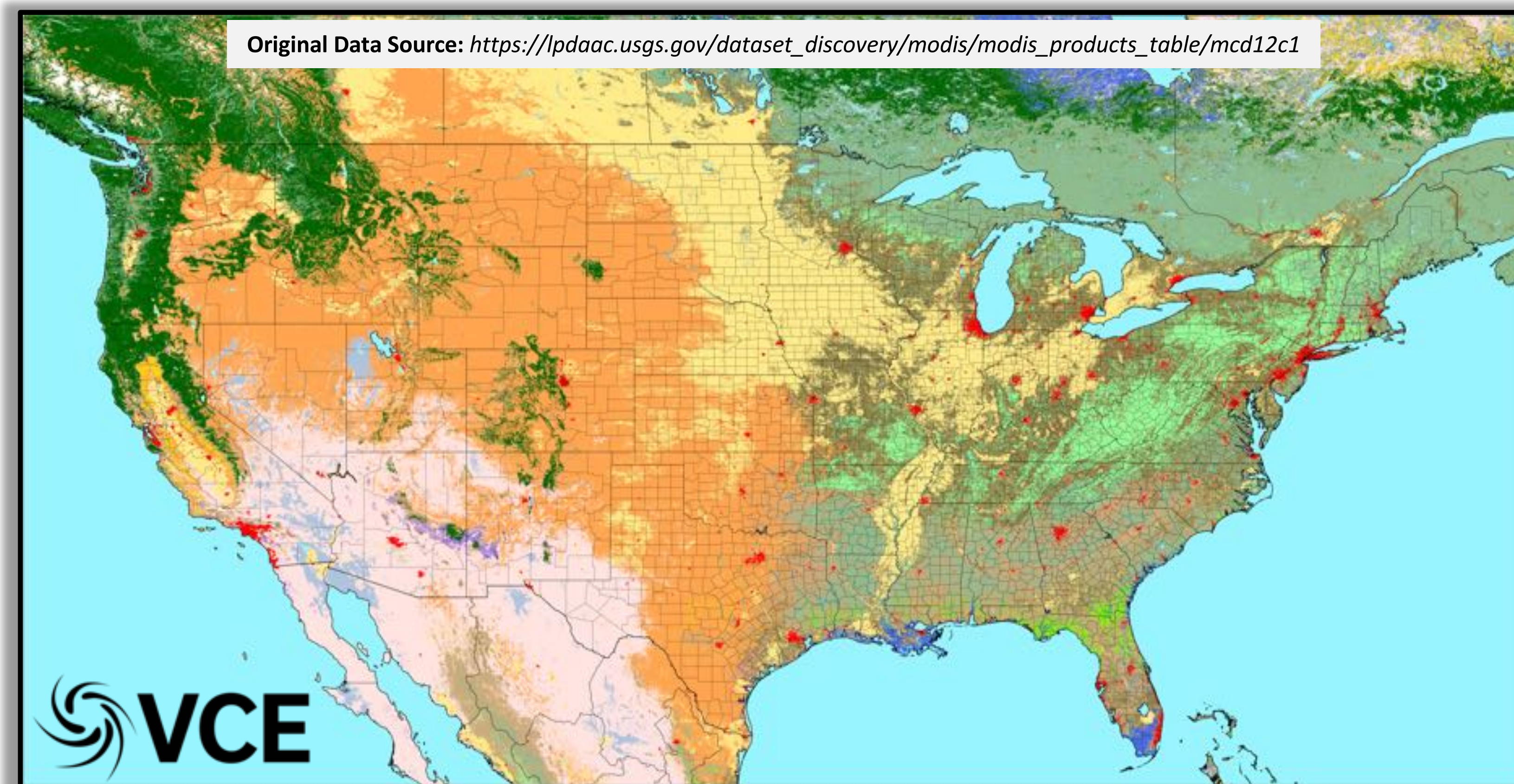
Existing Generators (2017)



Existing Electricity Transmission (2017)

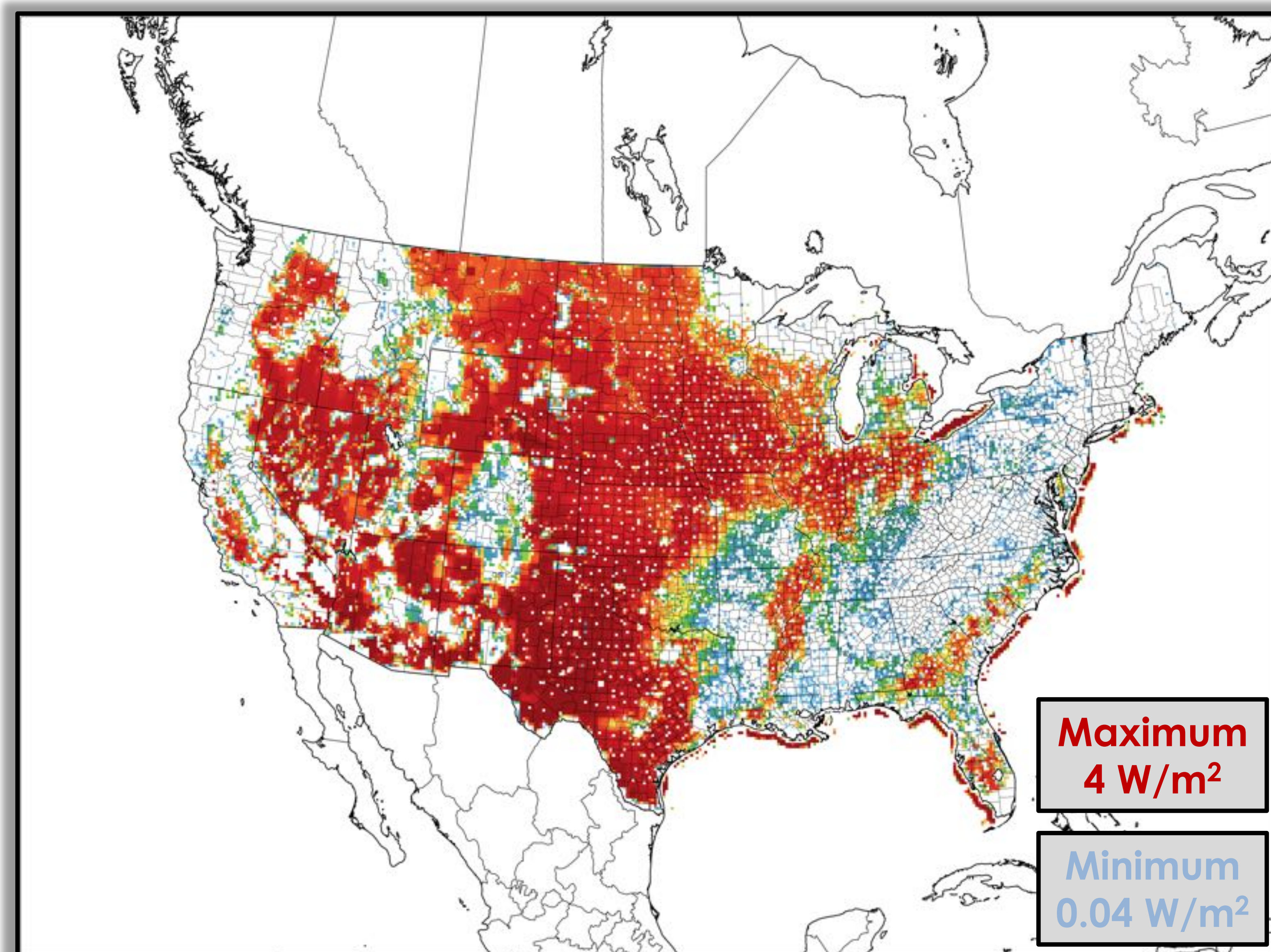


Land Use Dataset



- Water
- Evergreen NL Forest
- Evergreen BL Forest
- Deciduous NL Forest
- Deciduous BL Forest
- Mixed Forest
- Closed Shrubland
- Open Shrubland
- Woody Savanna
- Savanna
- Grassland
- Permanent Wetland
- Cropland
- Urban & Built up
- Crops & Natural Vegetation
- Snow & Ice
- Barren / Sparse
- Unclassified

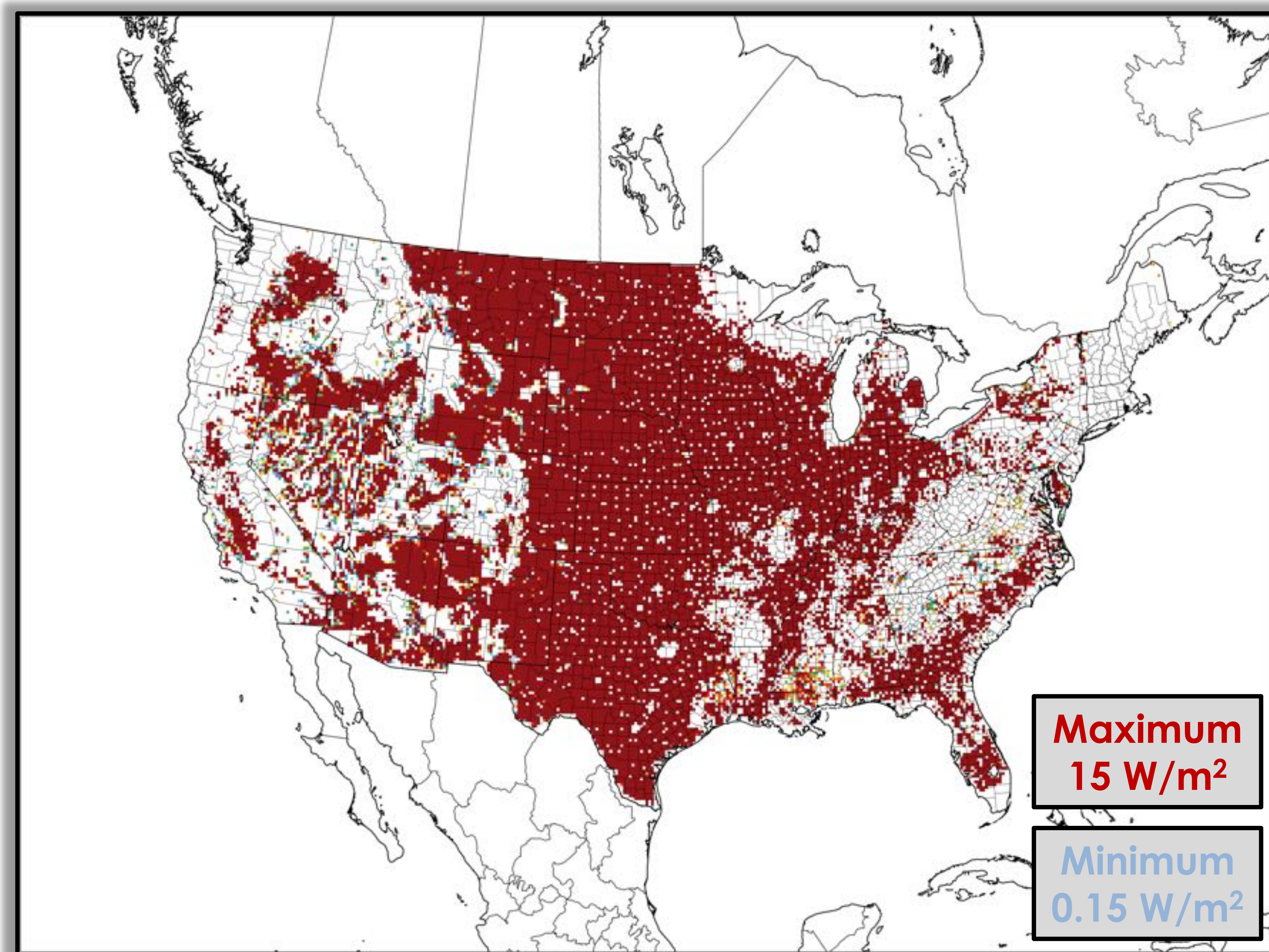
Strict Siting Constraints For Wind Turbines



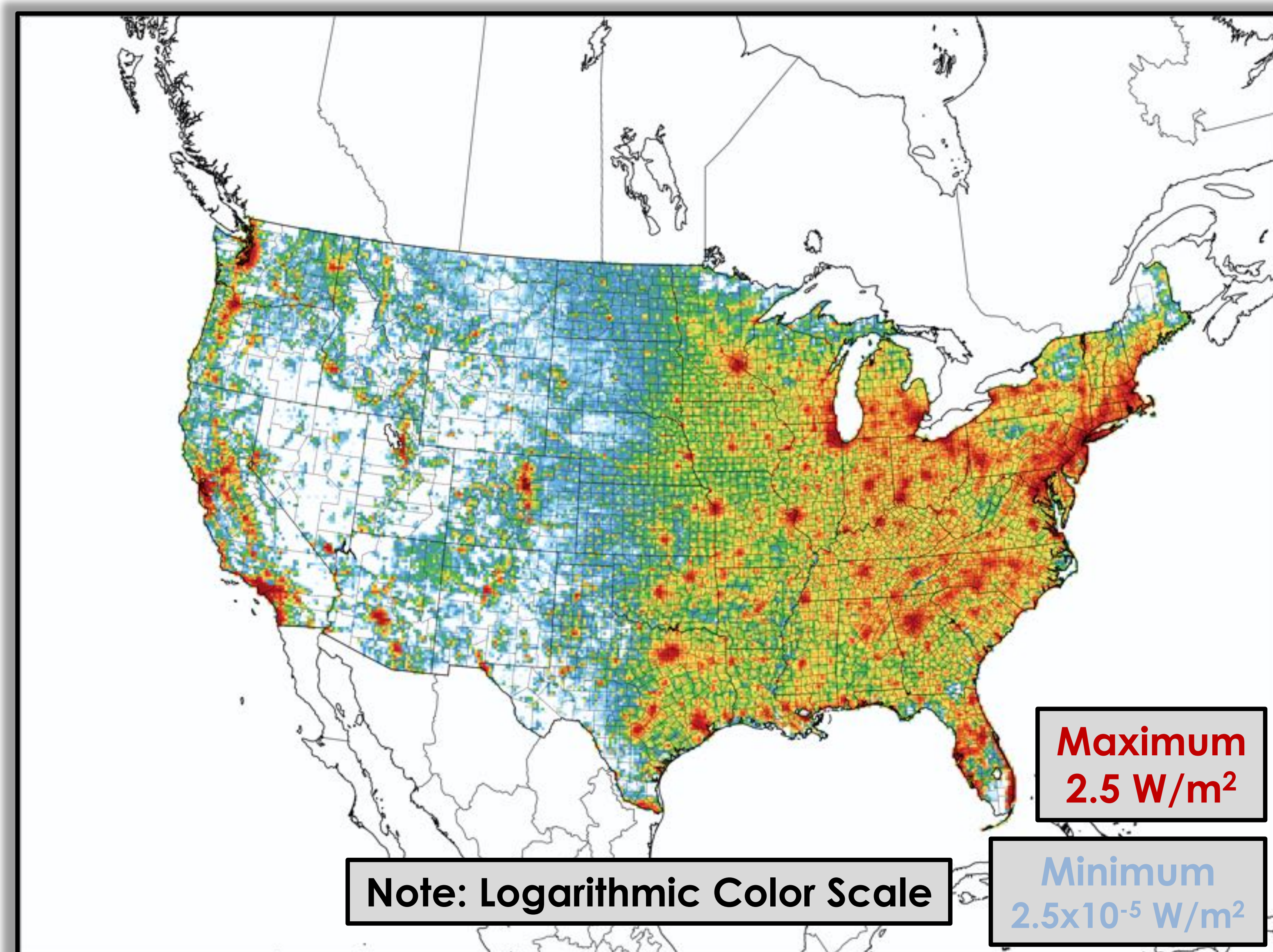
info@vibrantcleanenergy.com

VCE
VIBRANT CLEAN ENERGY

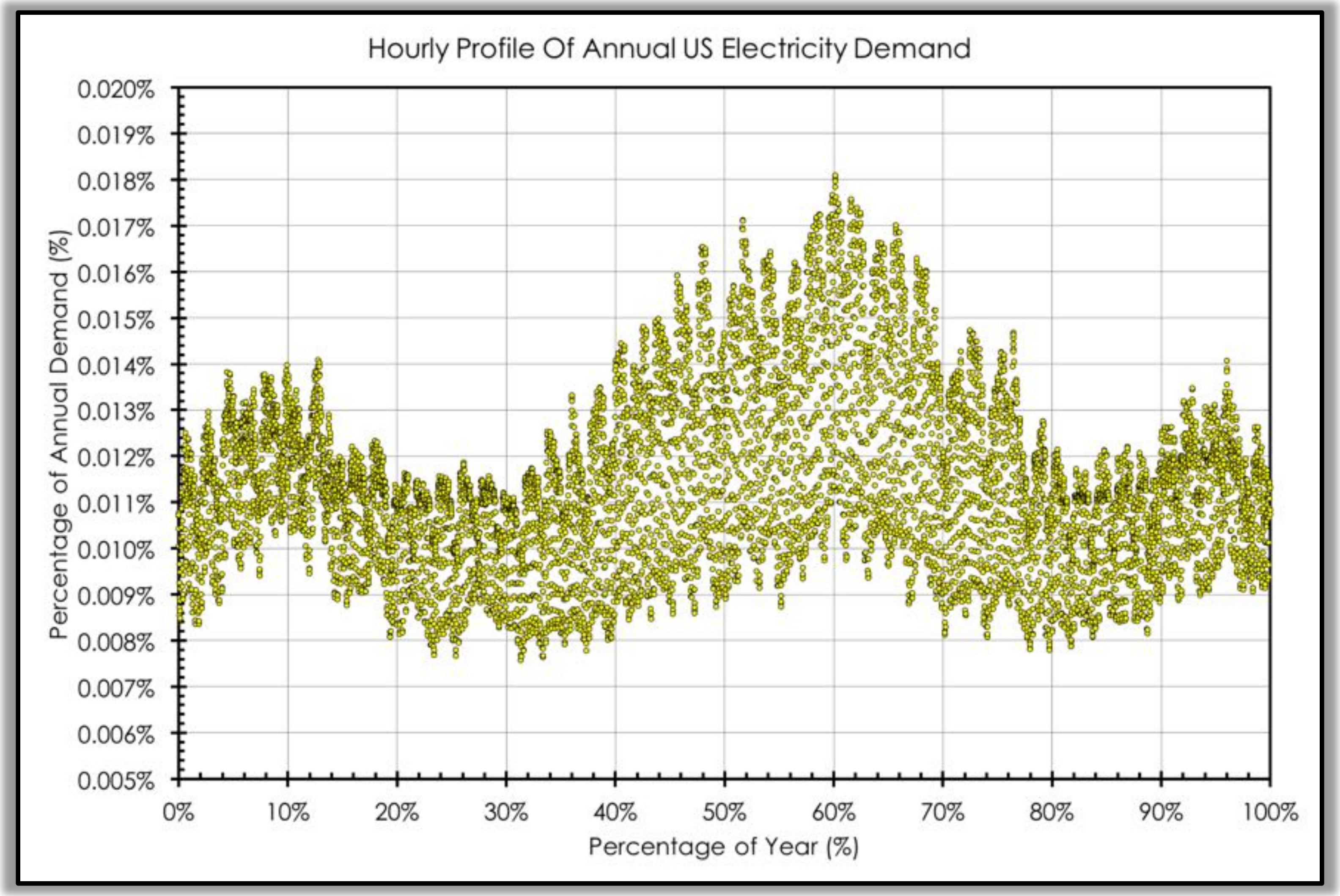
Strict Siting Constraints For Utility PV



Advanced Screening For Rooftop PV

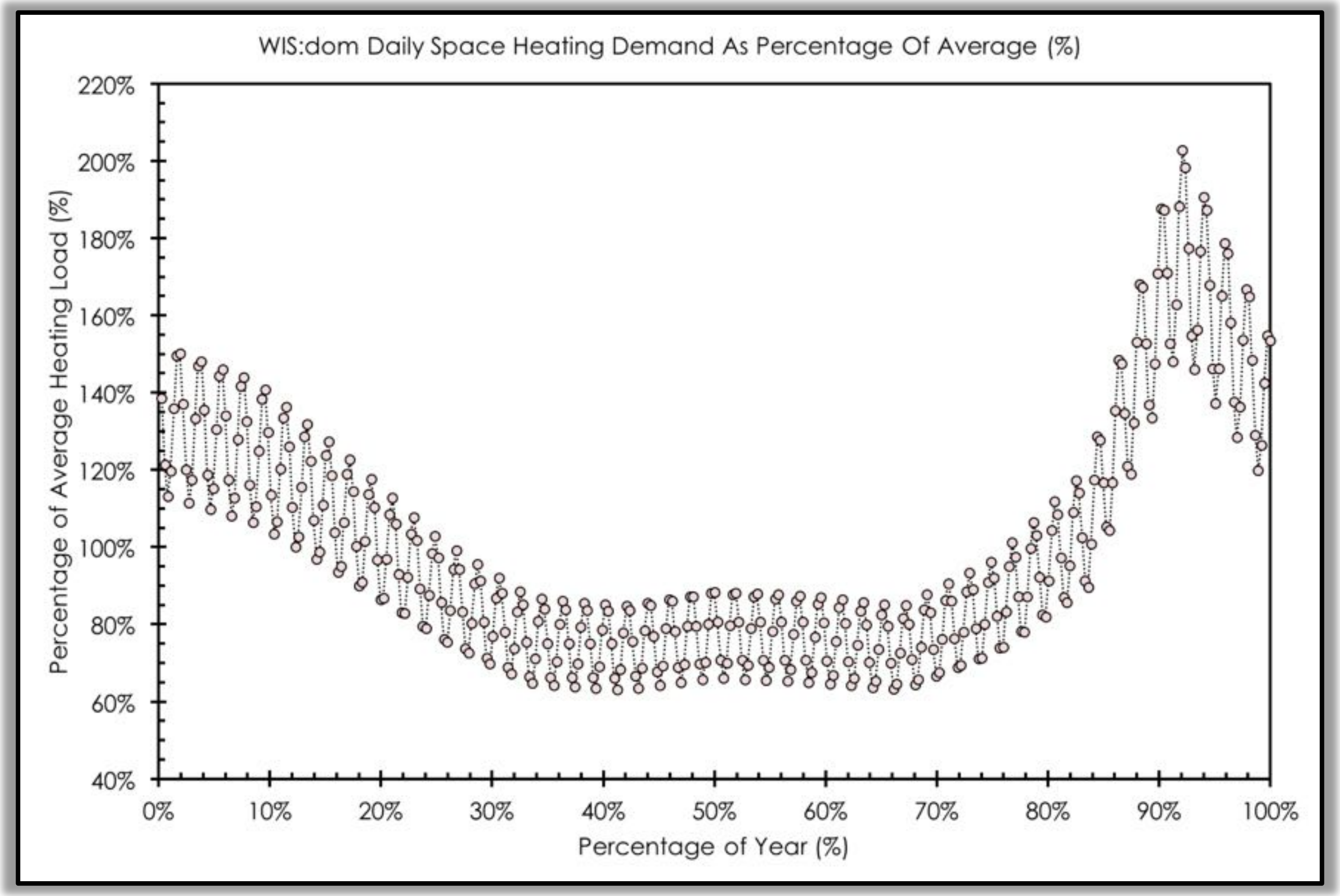


Load Initialization & Forecasts

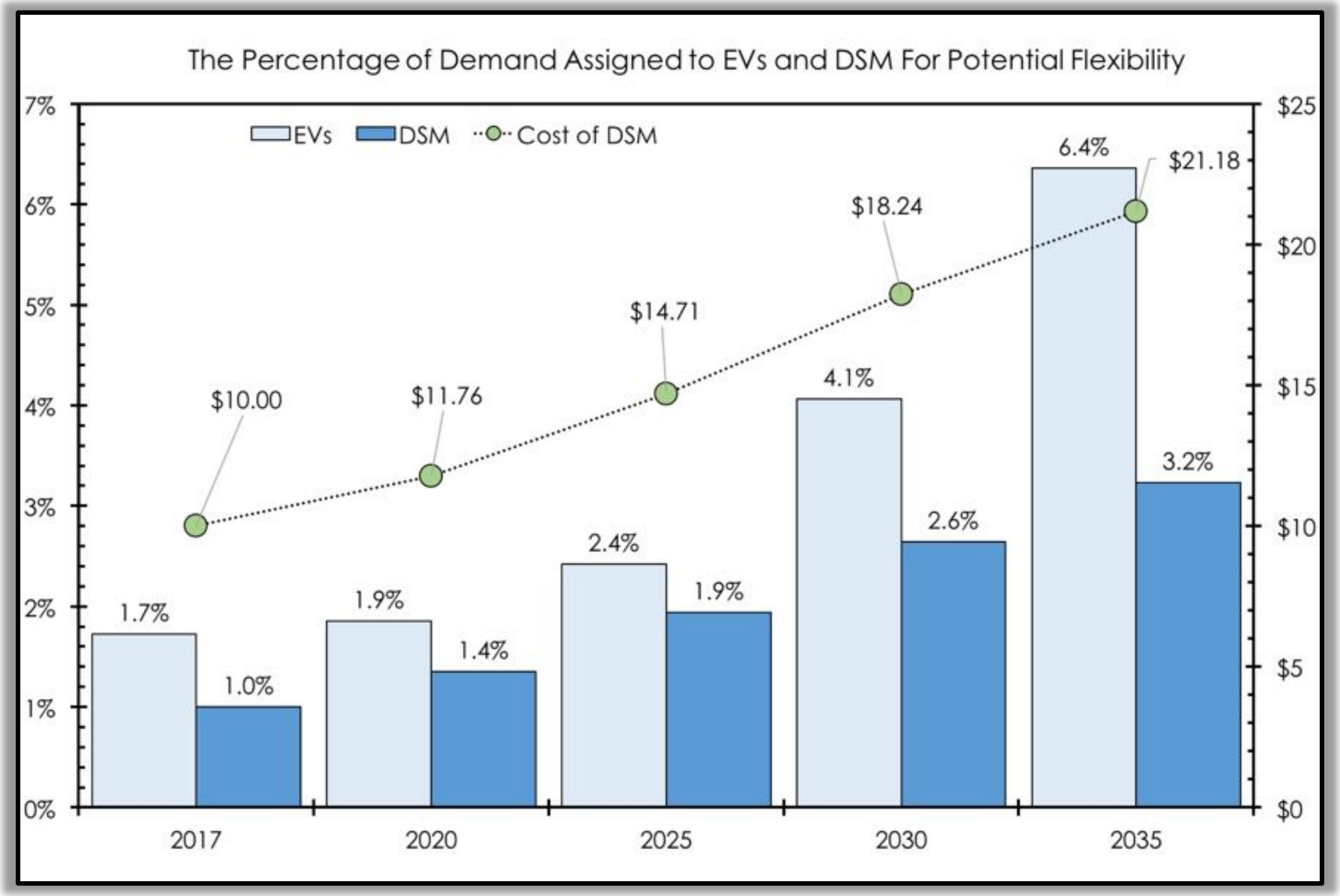


VCE VIBRANT CLEAN ENERGY

Load Initialization & Forecasts

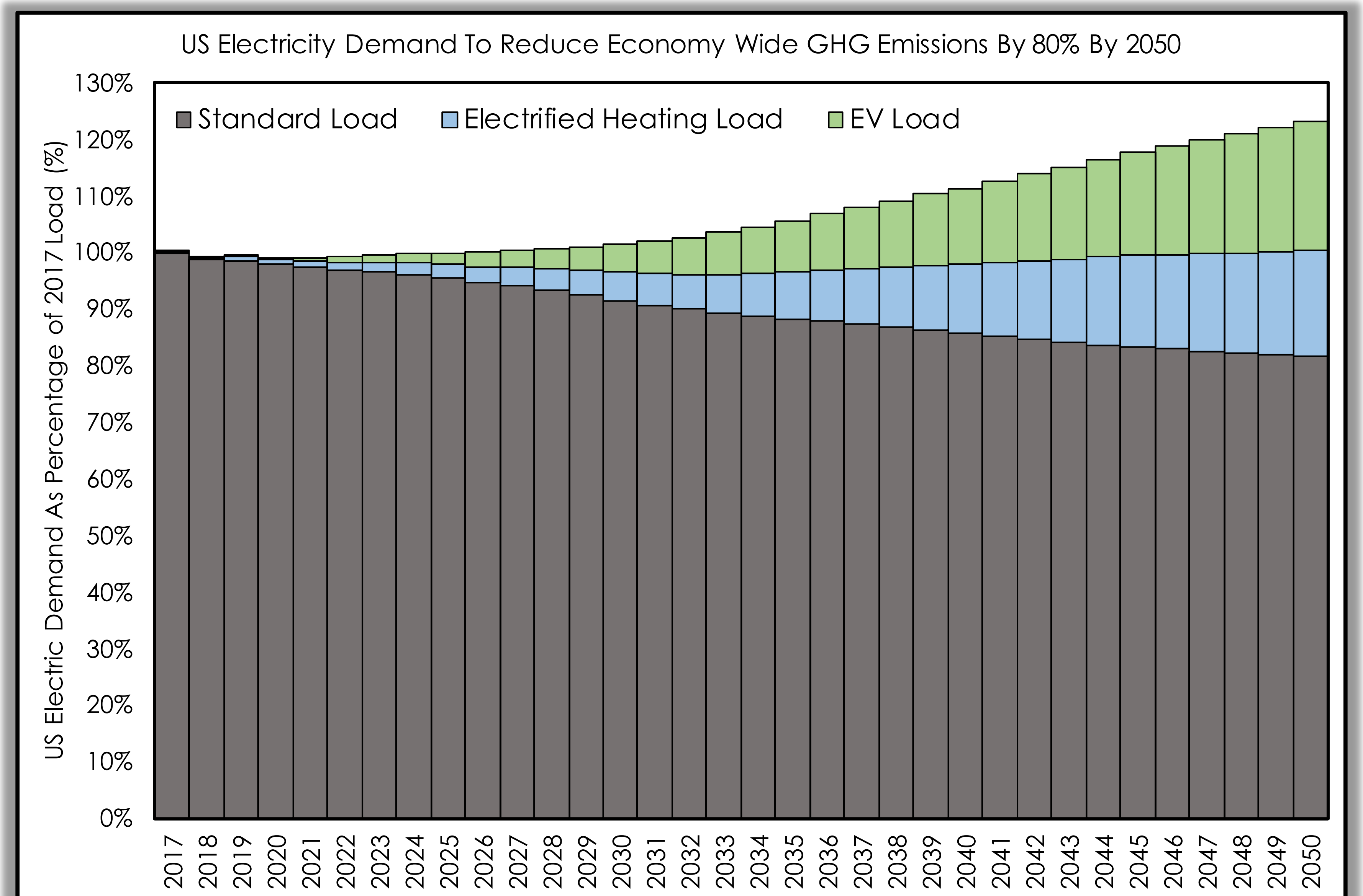


Demand Side Resources



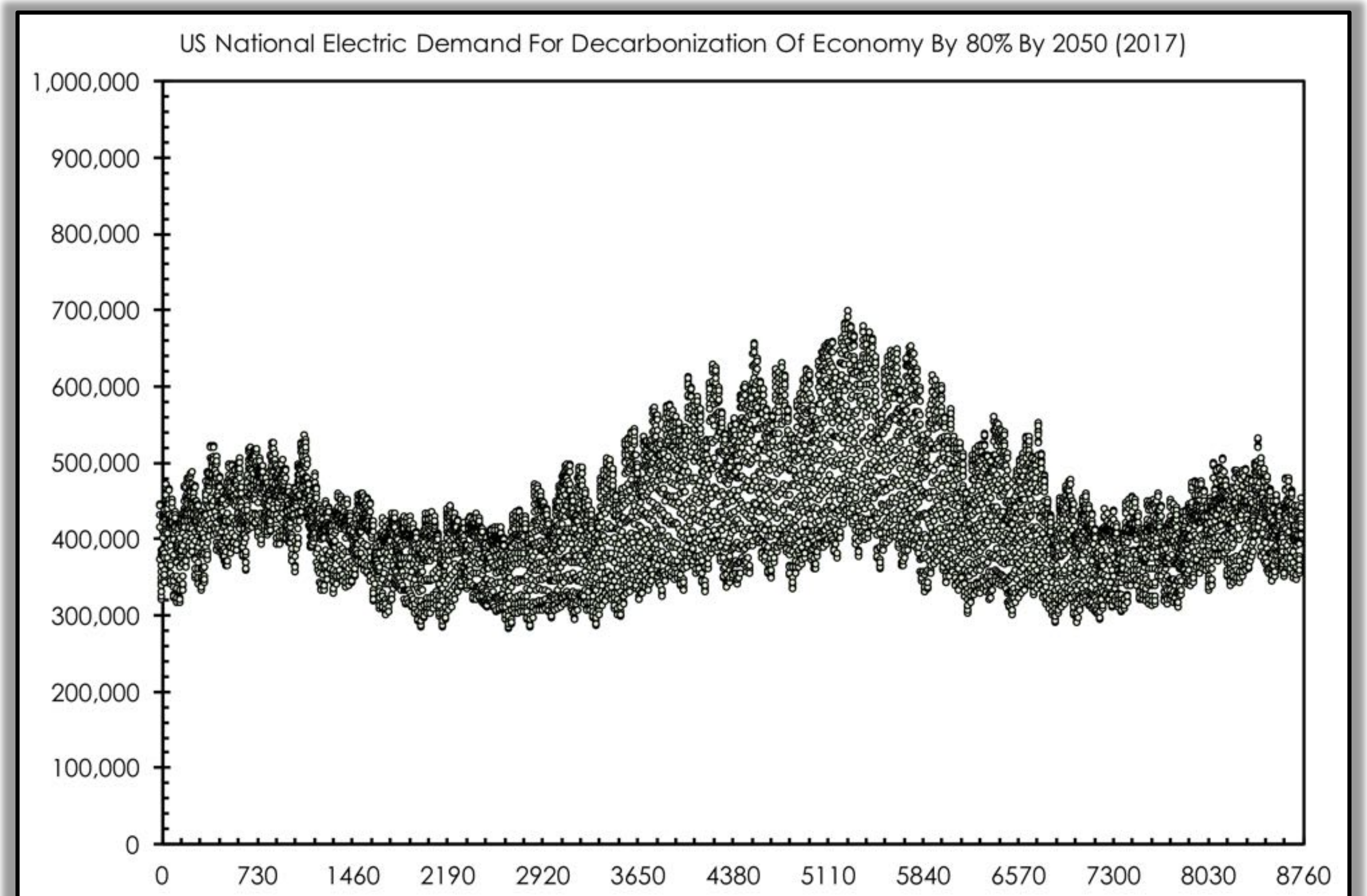
info@vibrantcleanenergy.com

Load Initialization & Forecasts

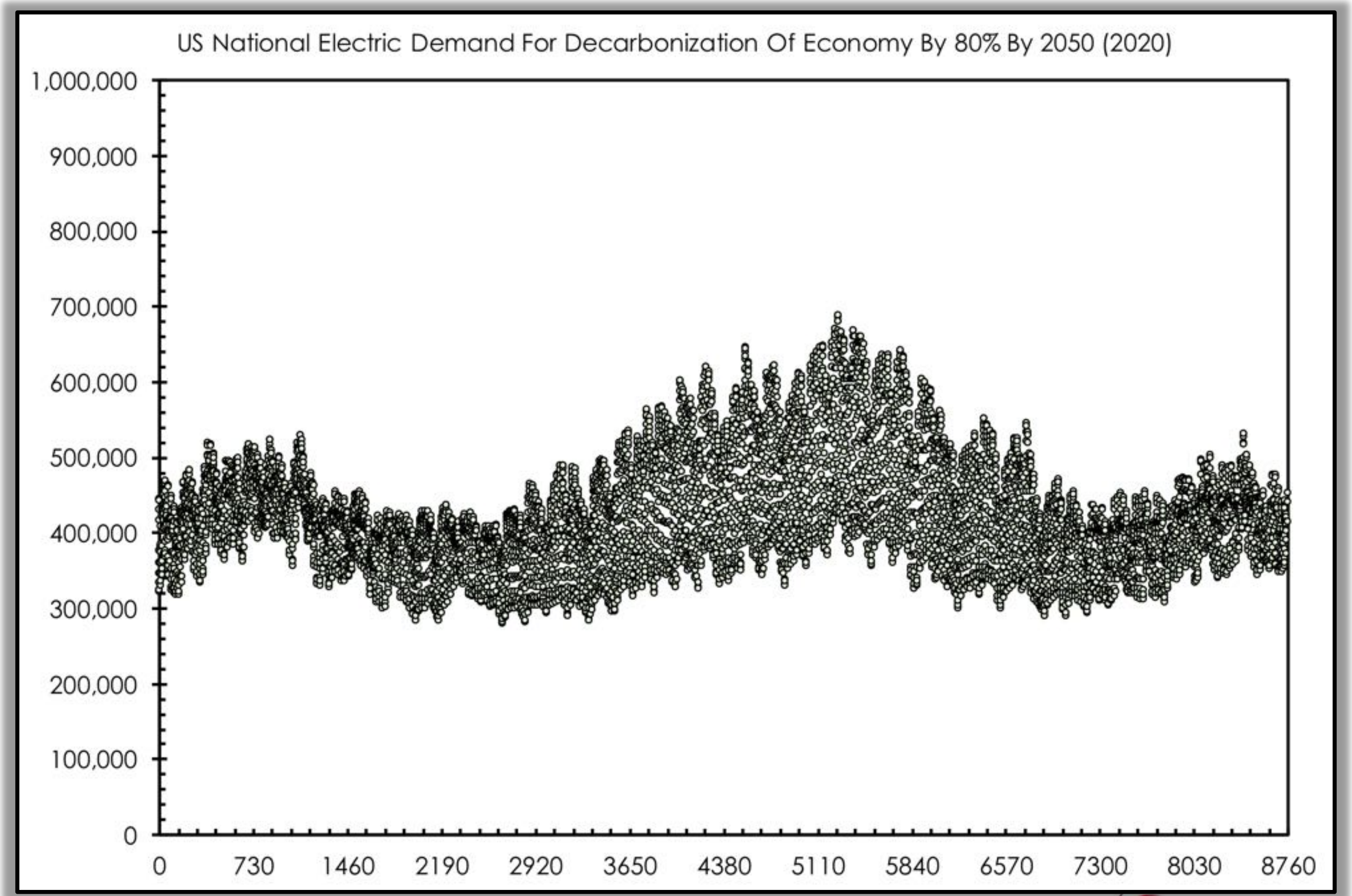


VIBRANT CLEAN ENERGY

Load Initialization & Forecasts



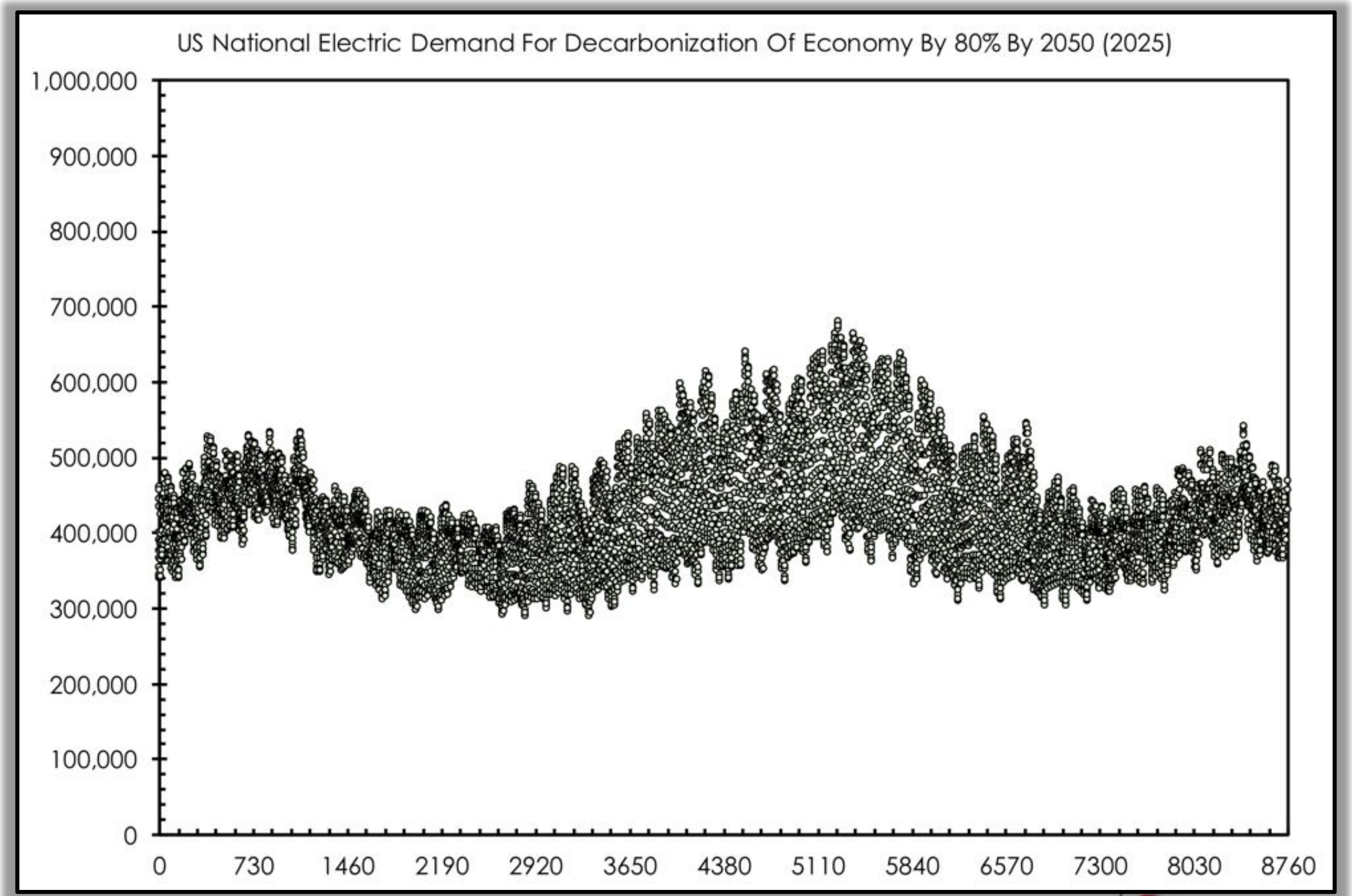
Load Initialization & Forecasts



info@vibrantcleanenergy.com

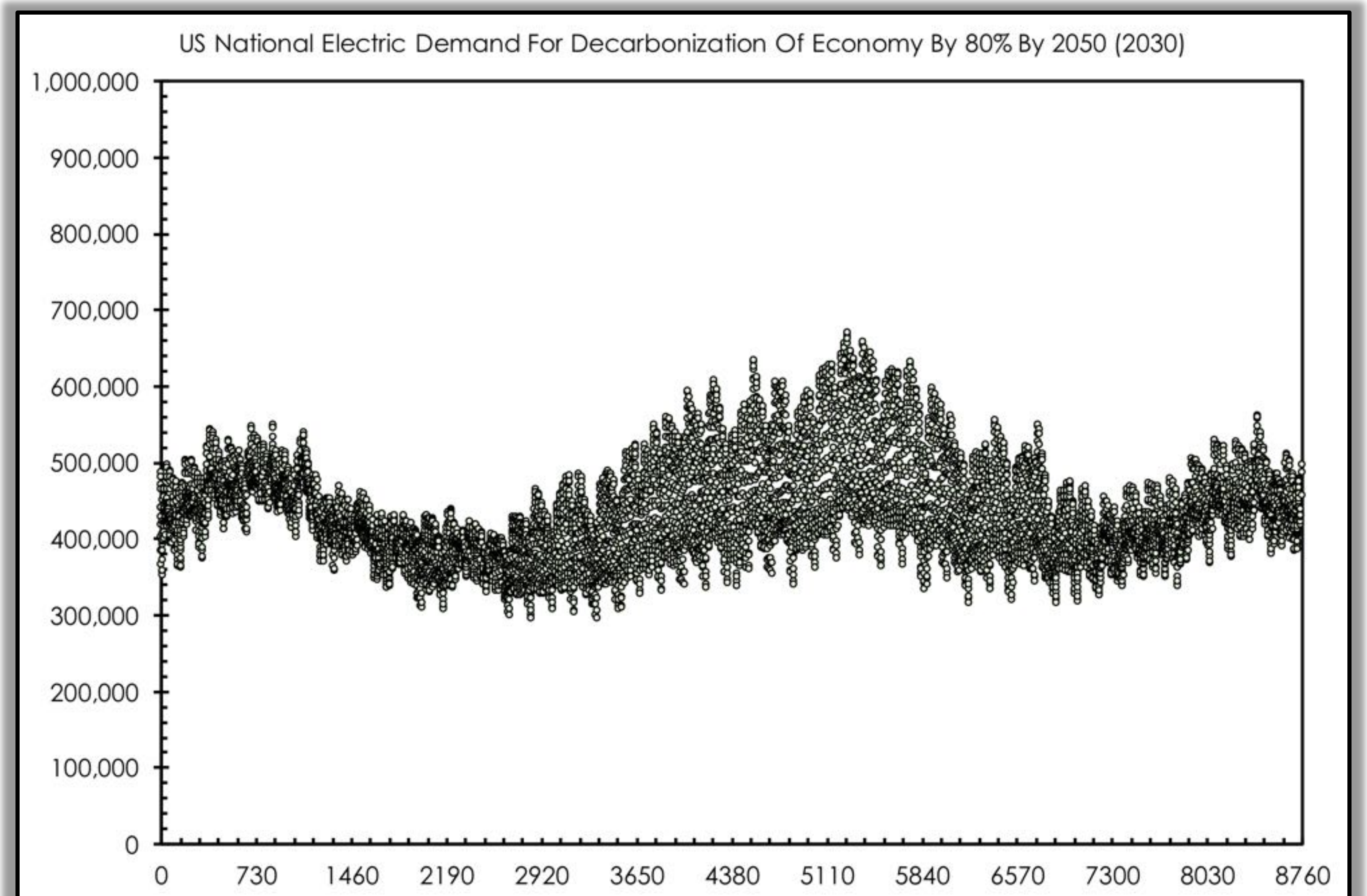
VCE
VIBRANT CLEAN ENERGY

Load Initialization & Forecasts

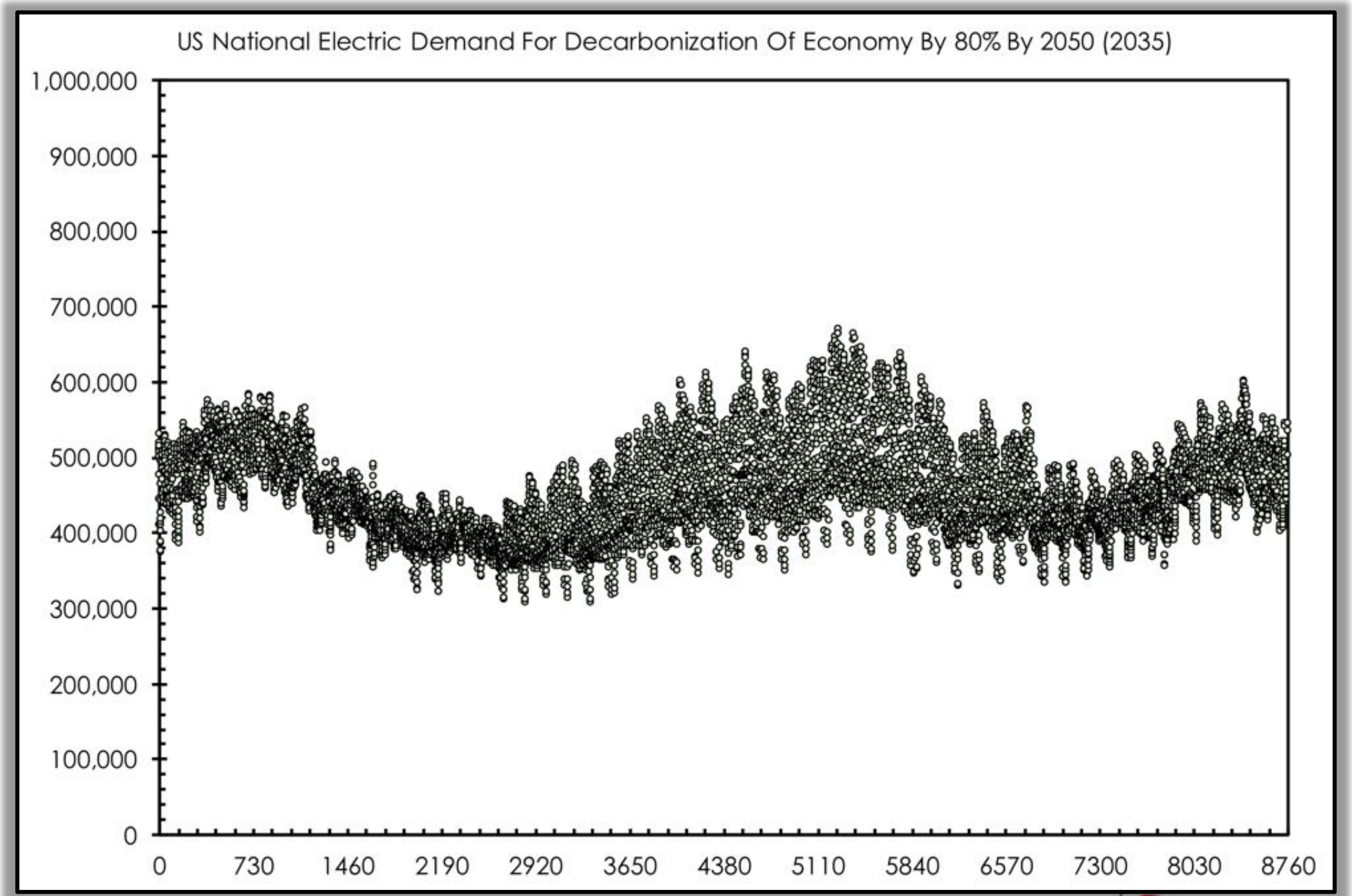


VCE
VIBRANT CLEAN ENERGY

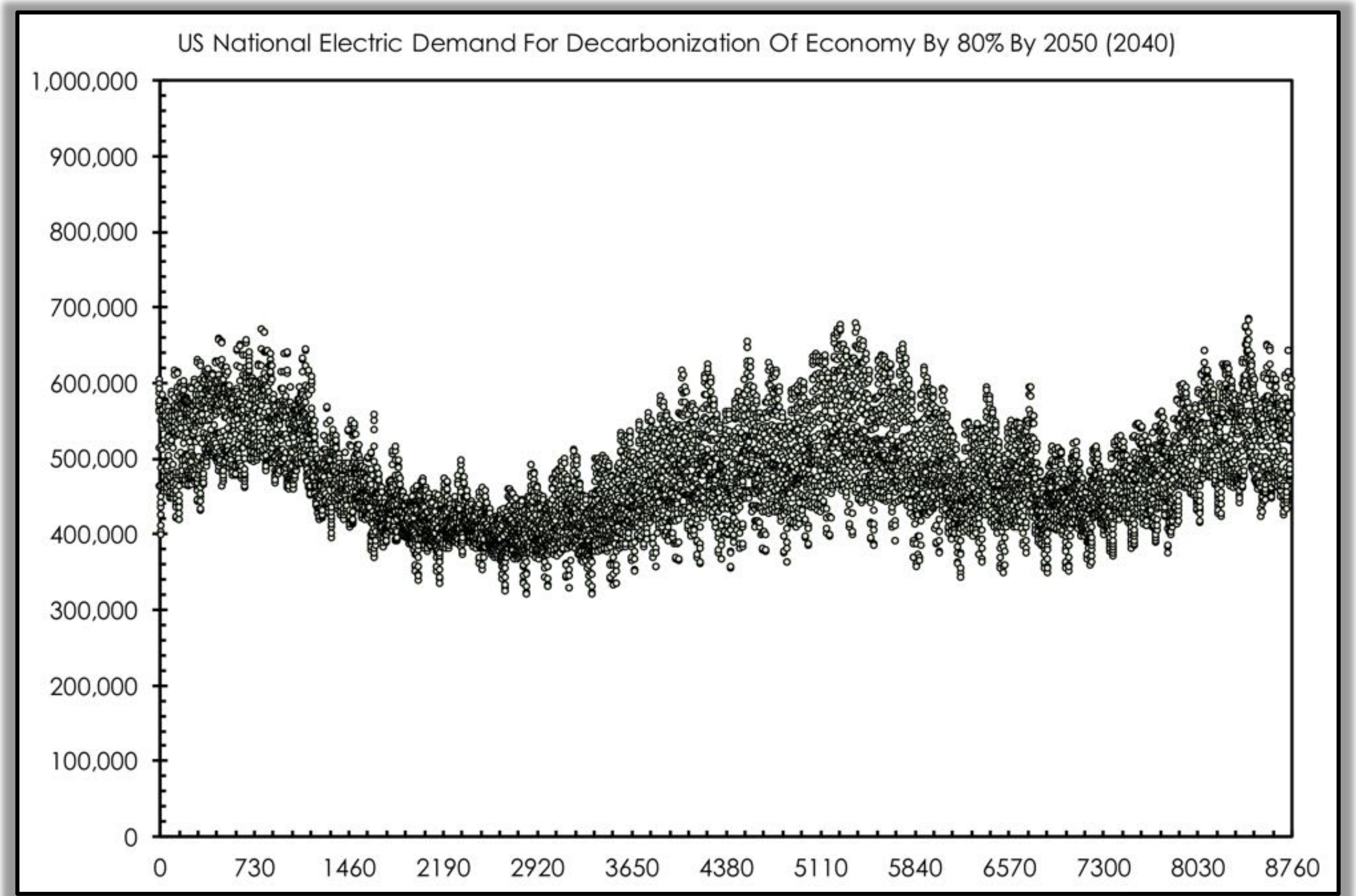
Load Initialization & Forecasts



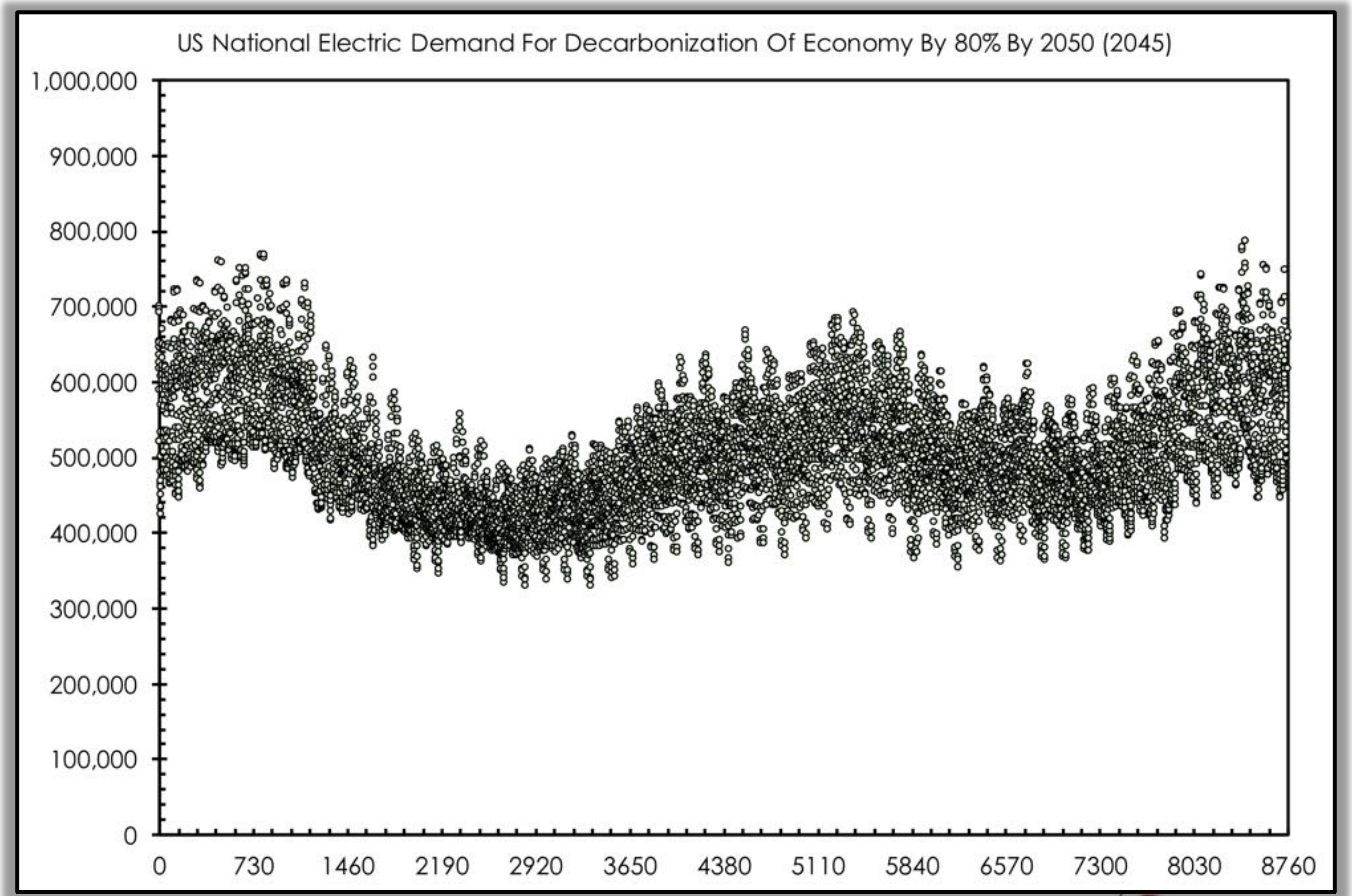
Load Initialization & Forecasts



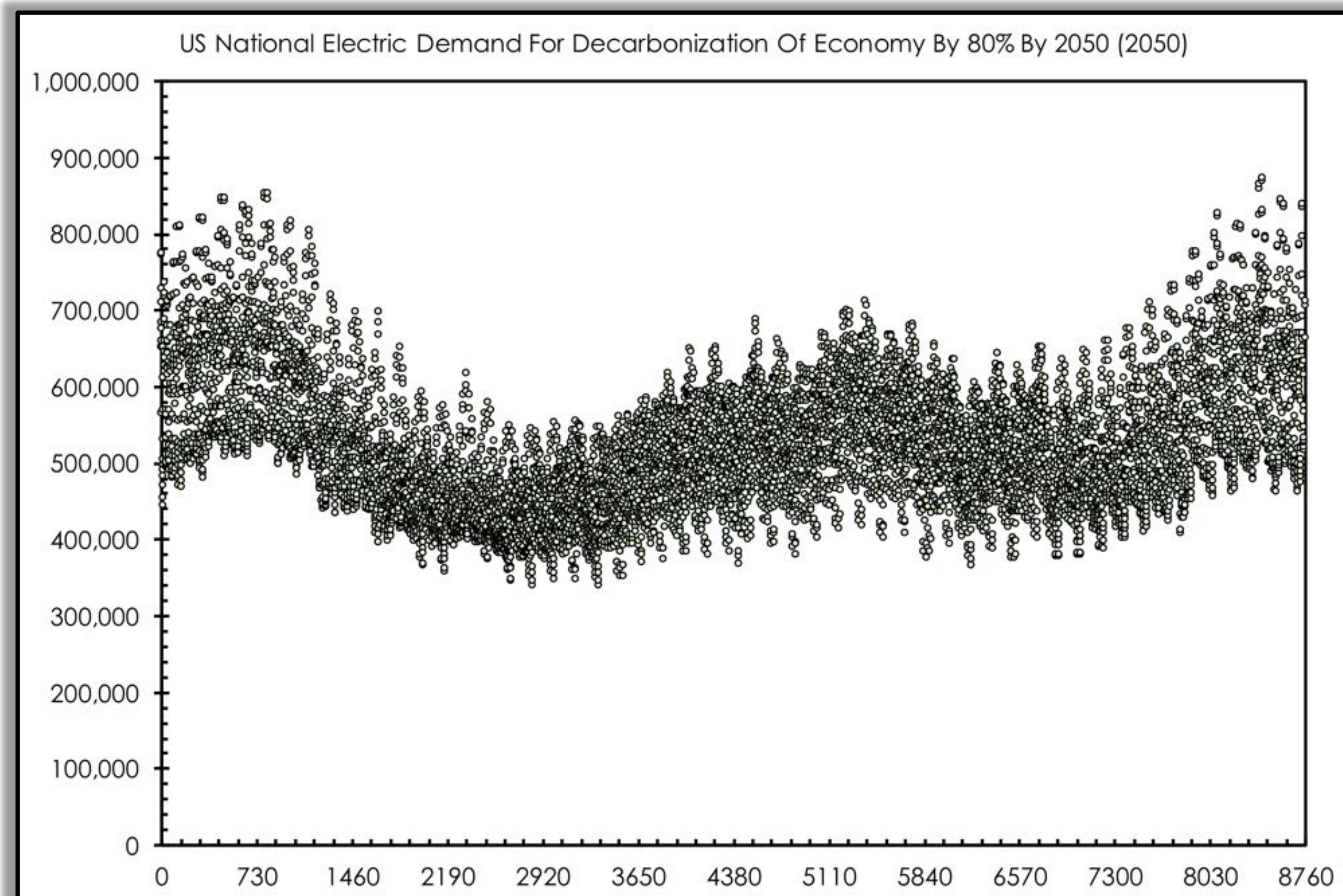
Load Initialization & Forecasts



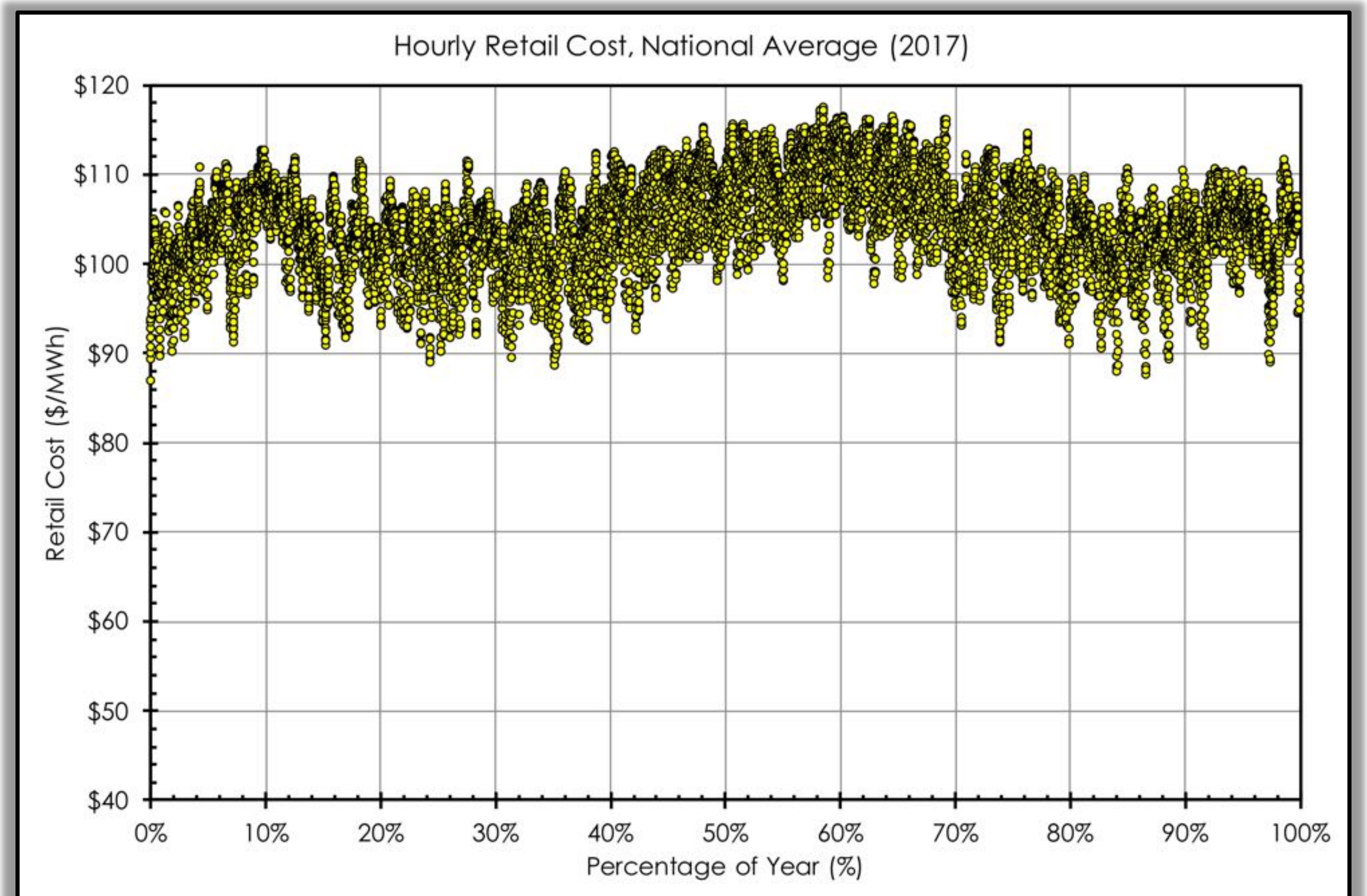
Load Initialization & Forecasts



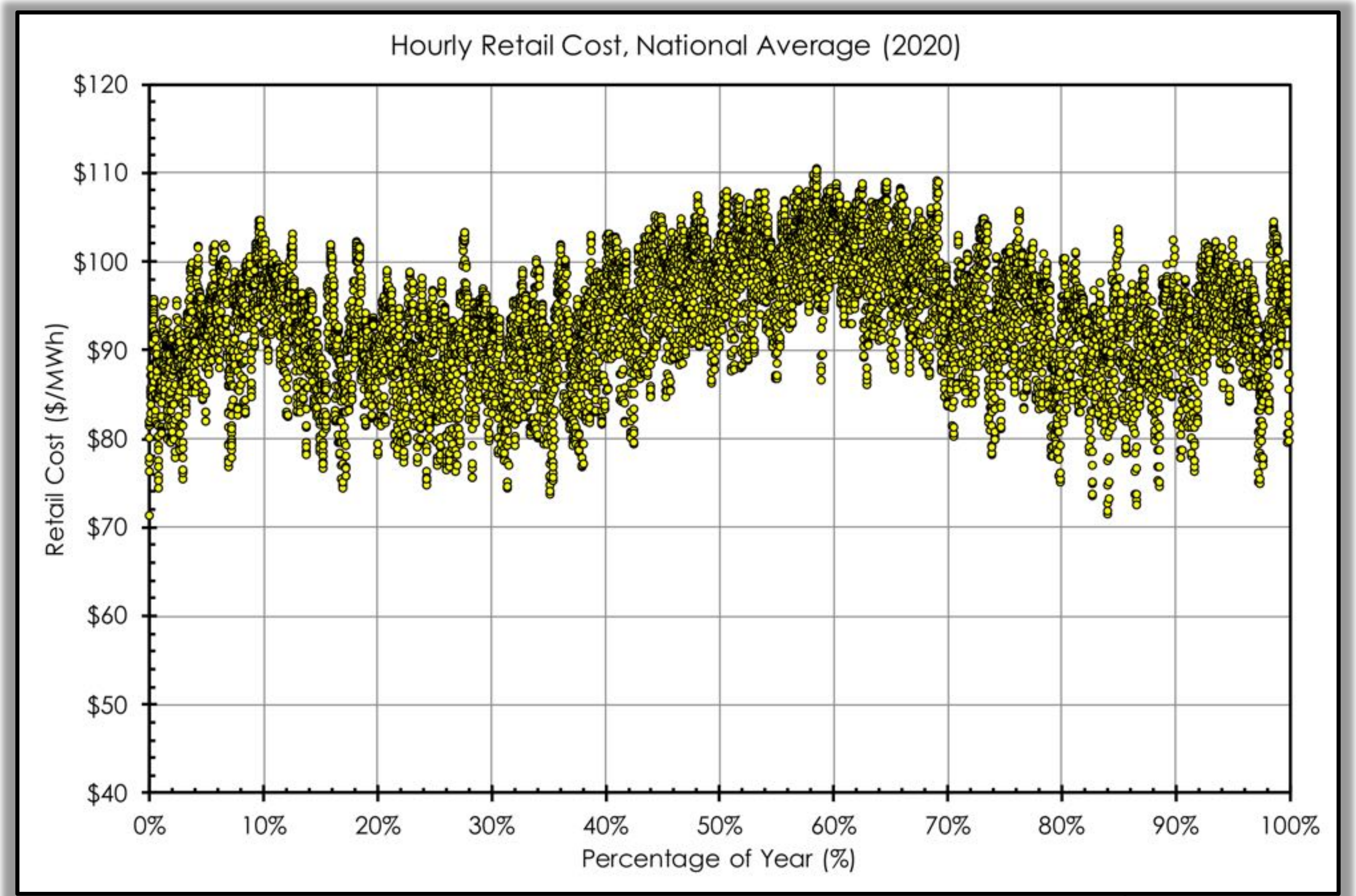
Load Initialization & Forecasts



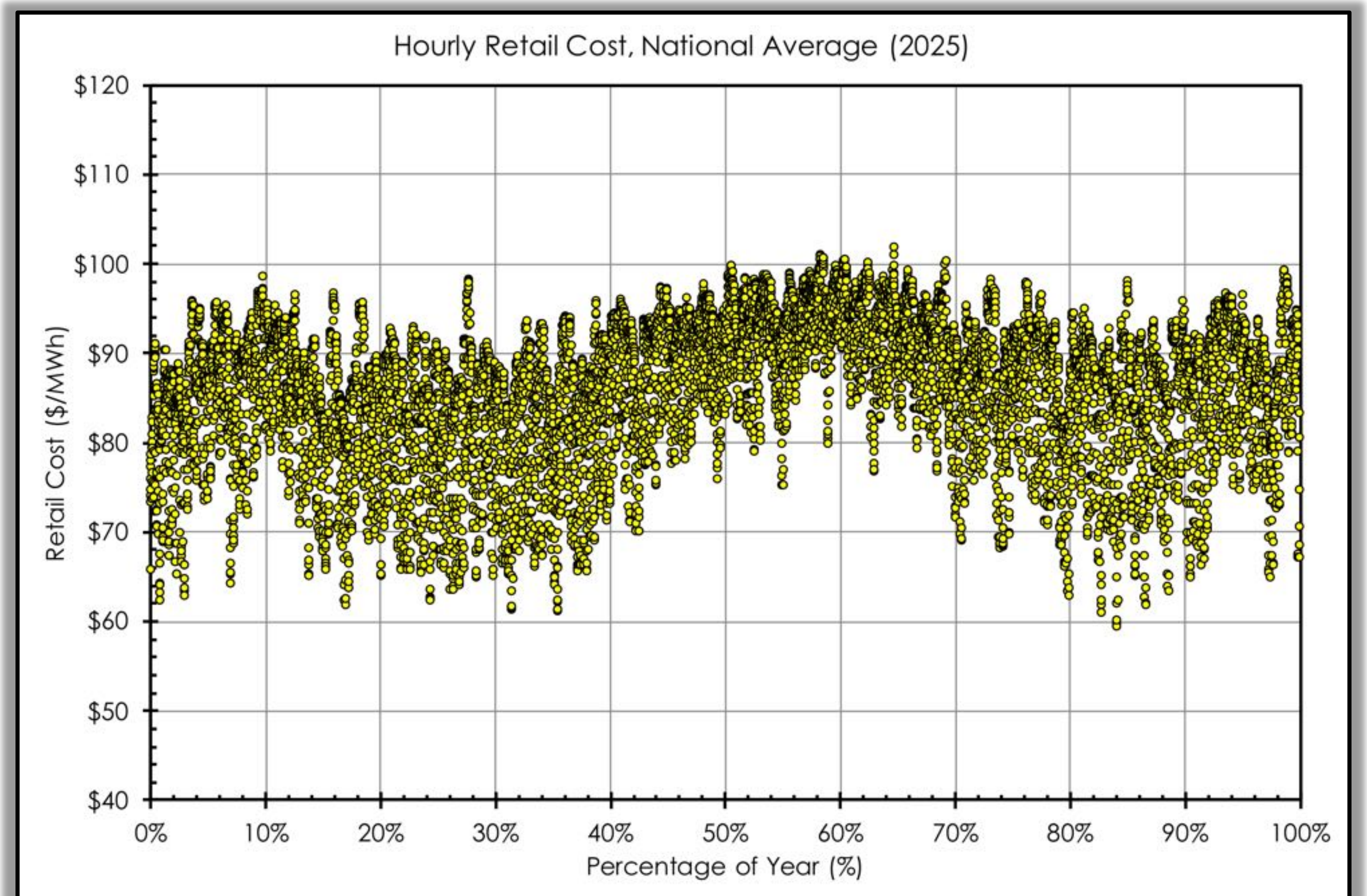
How Costs Change In the Future



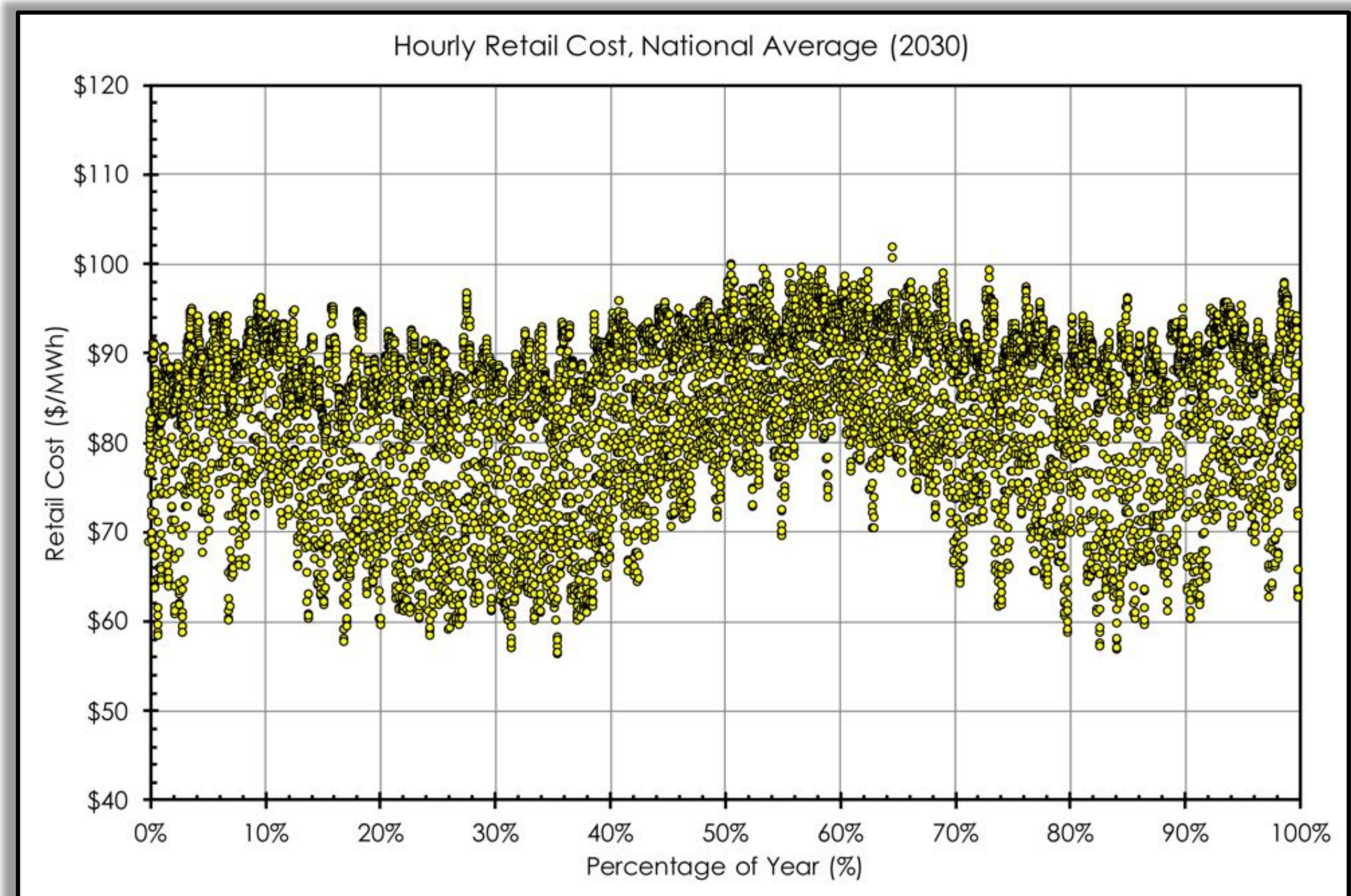
How Costs Change In the Future



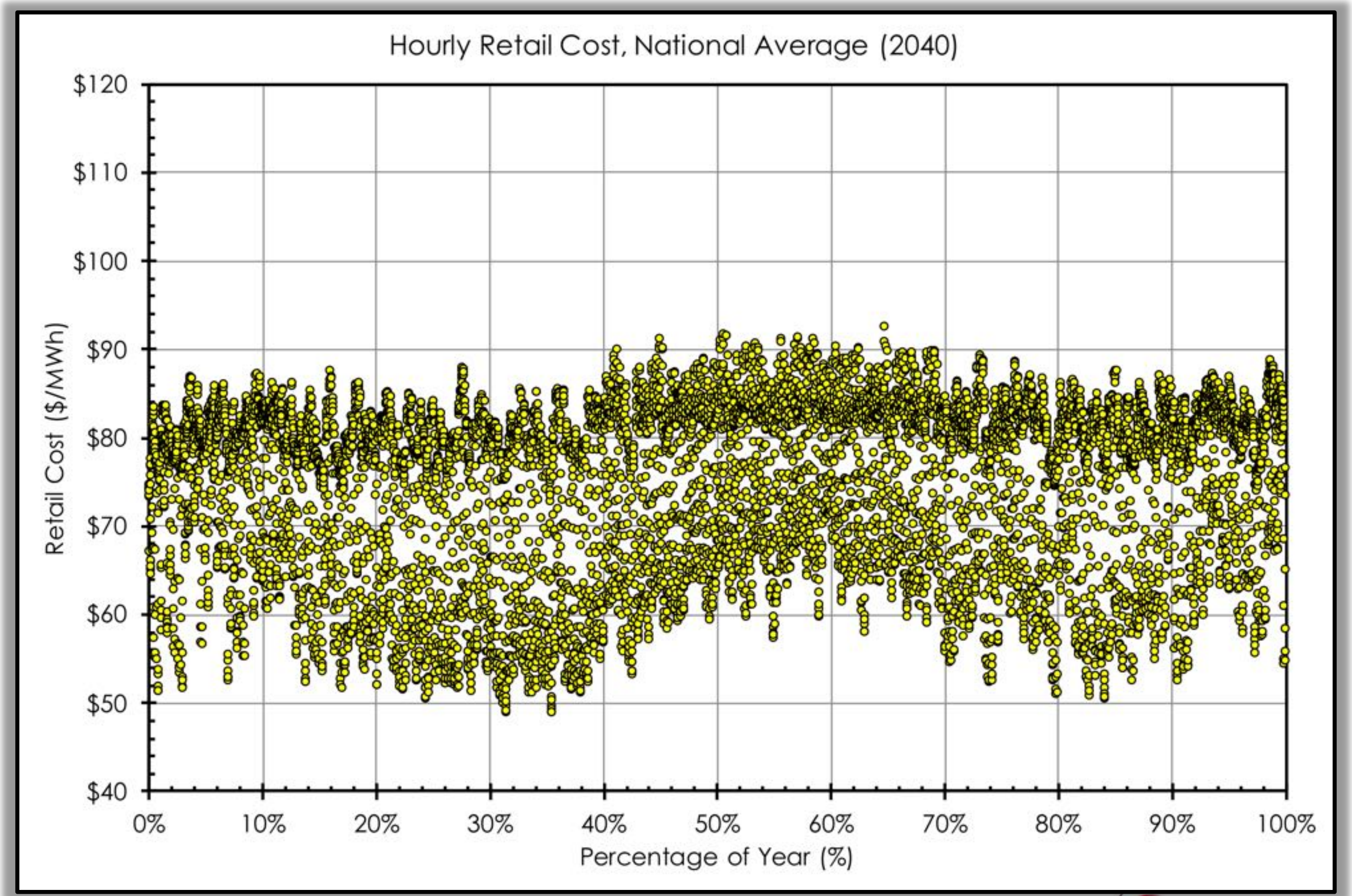
How Costs Change In the Future



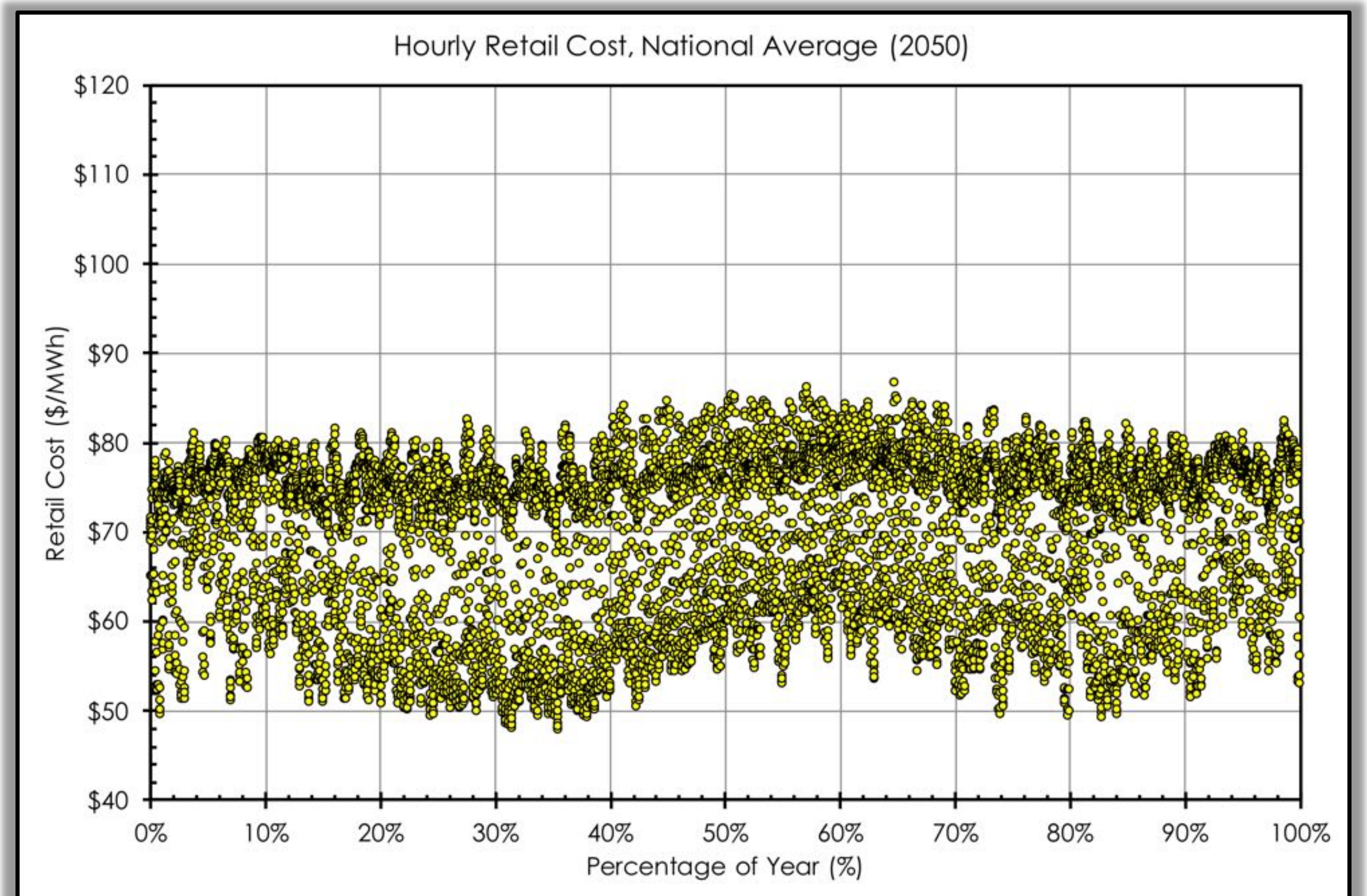
How Costs Change In the Future



How Costs Change In the Future

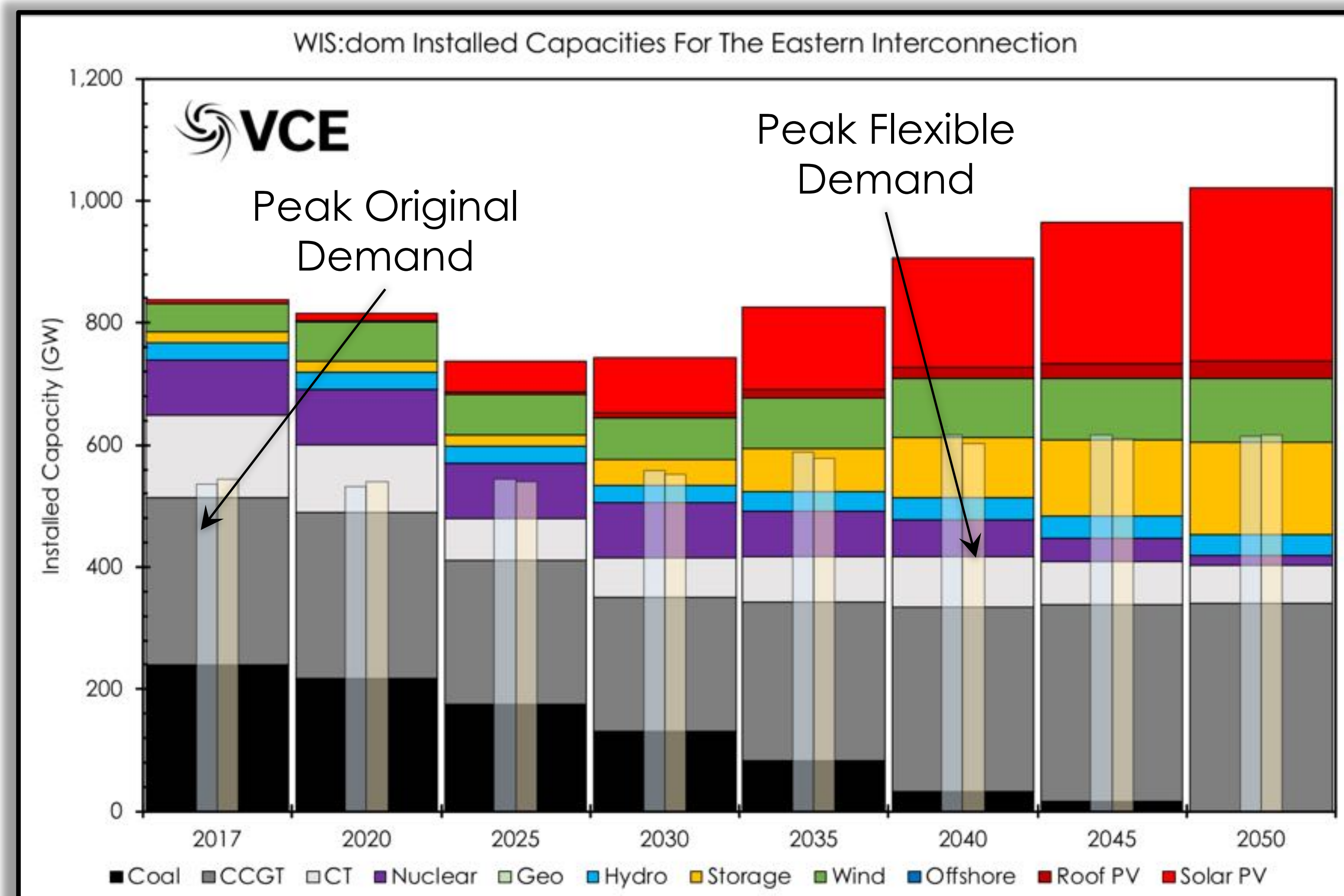


How Costs Change In the Future

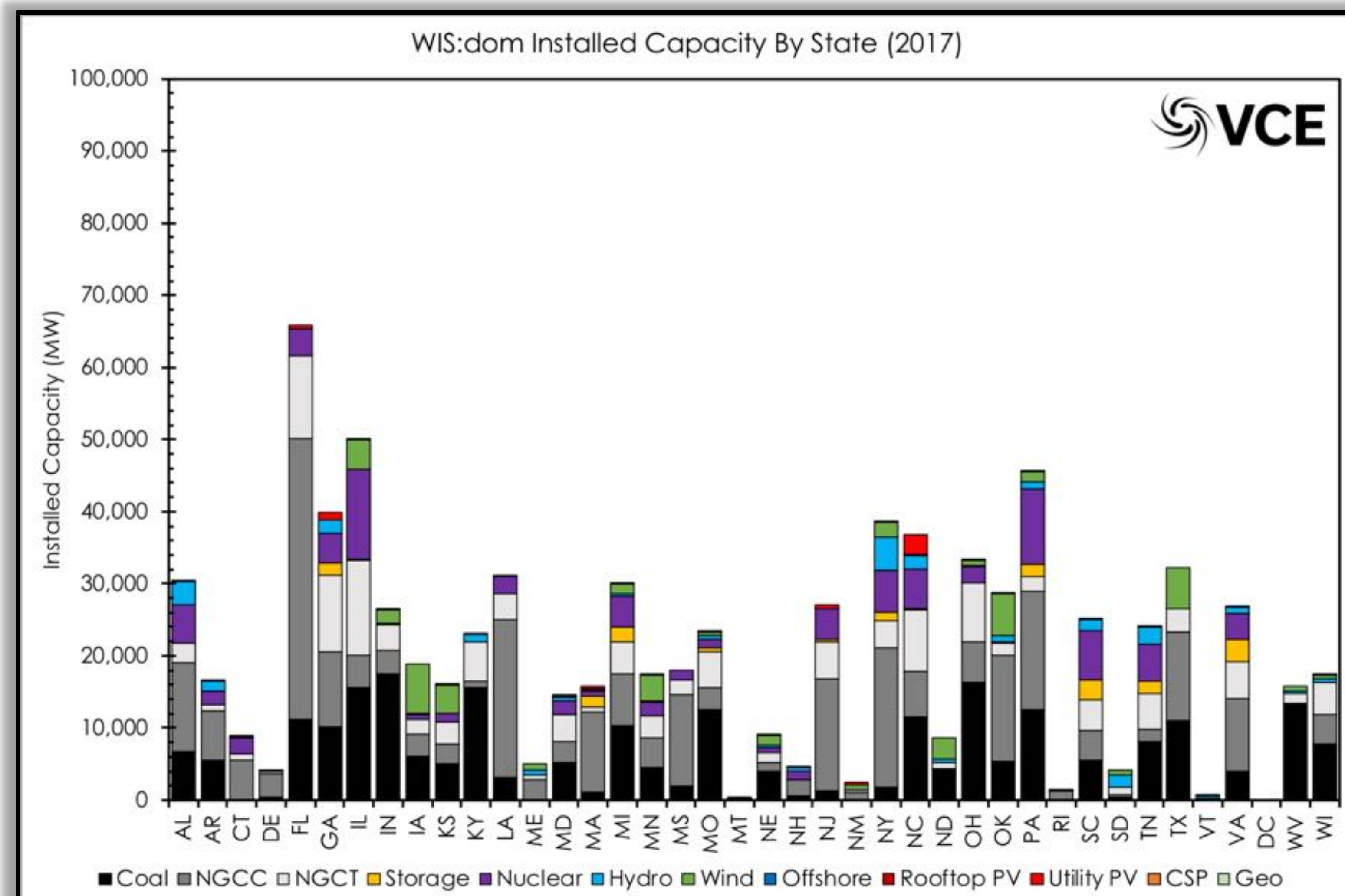


Example:
Eastern Interconnection Study

Installed Capacities

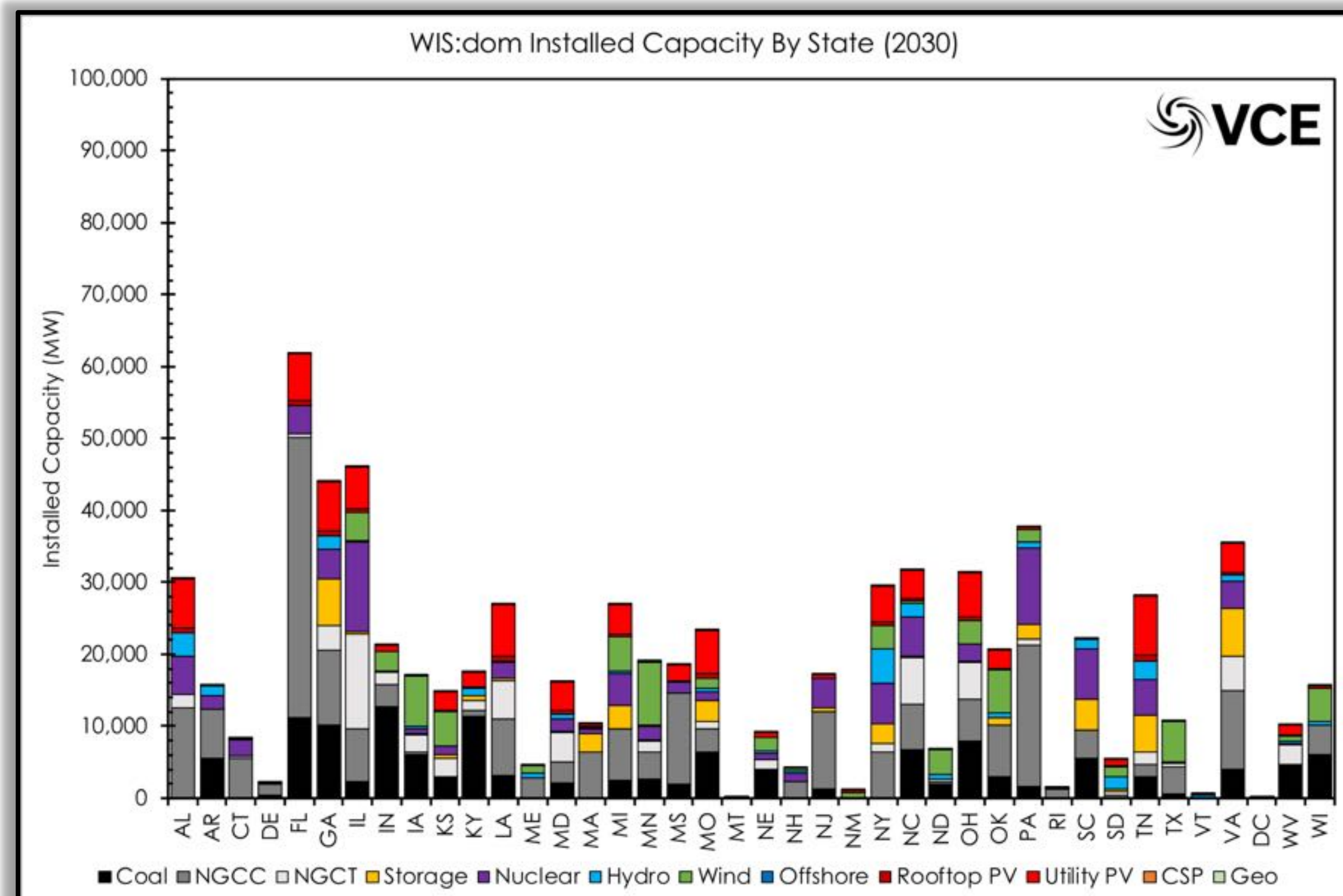


Installed Capacities

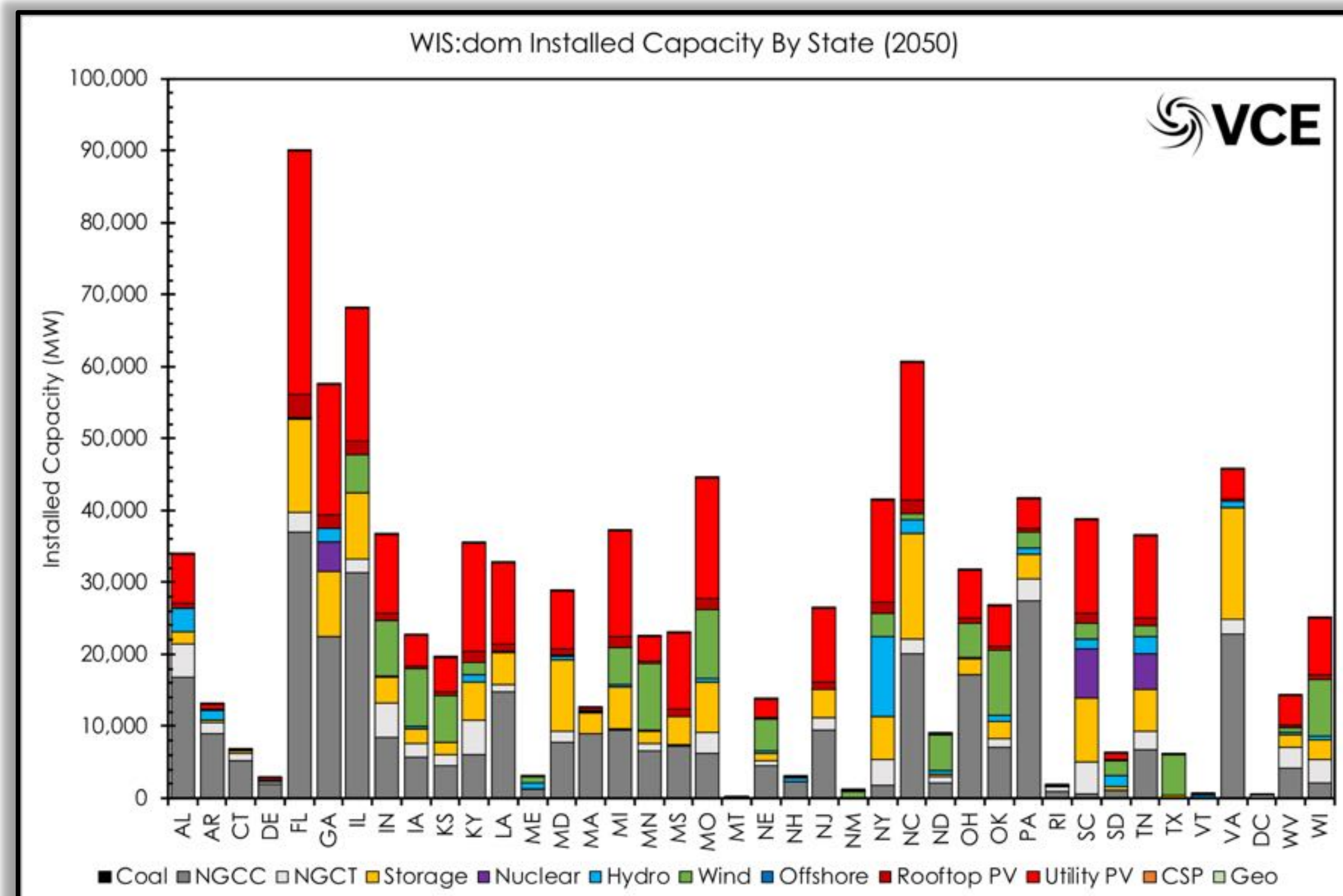


VIBRANT CLEAN ENERGY

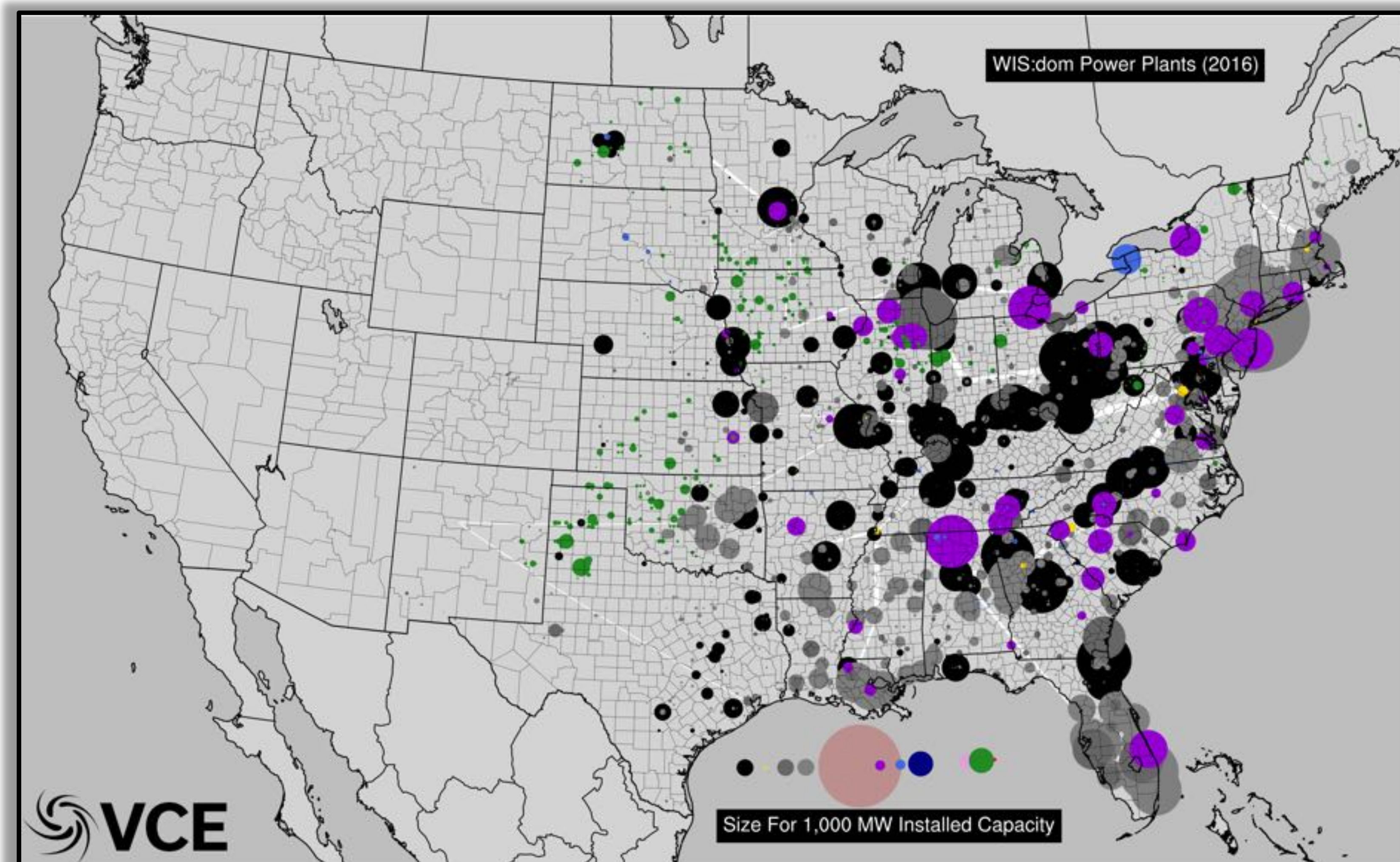
Installed Capacities



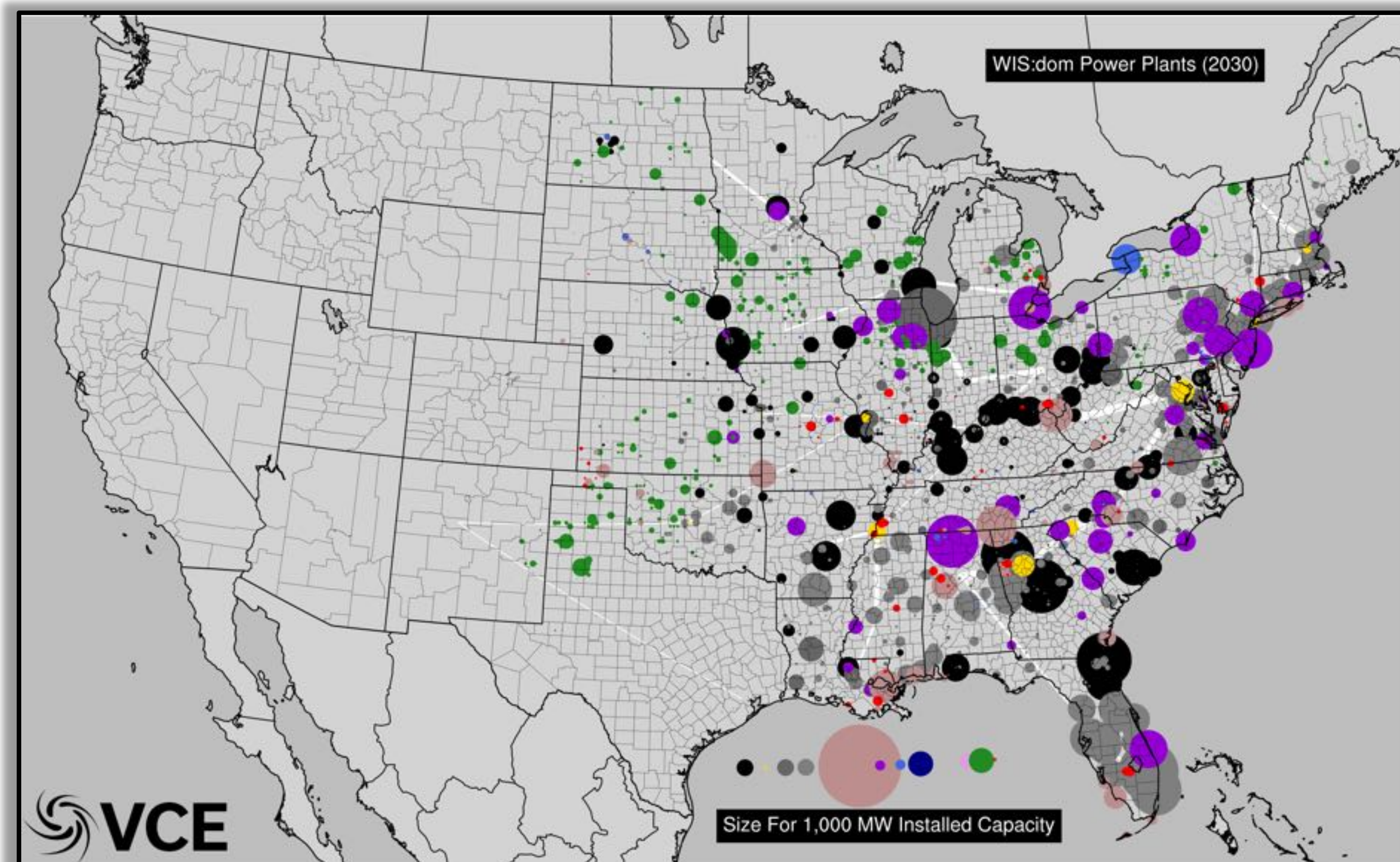
Installed Capacities



Installed Capacities

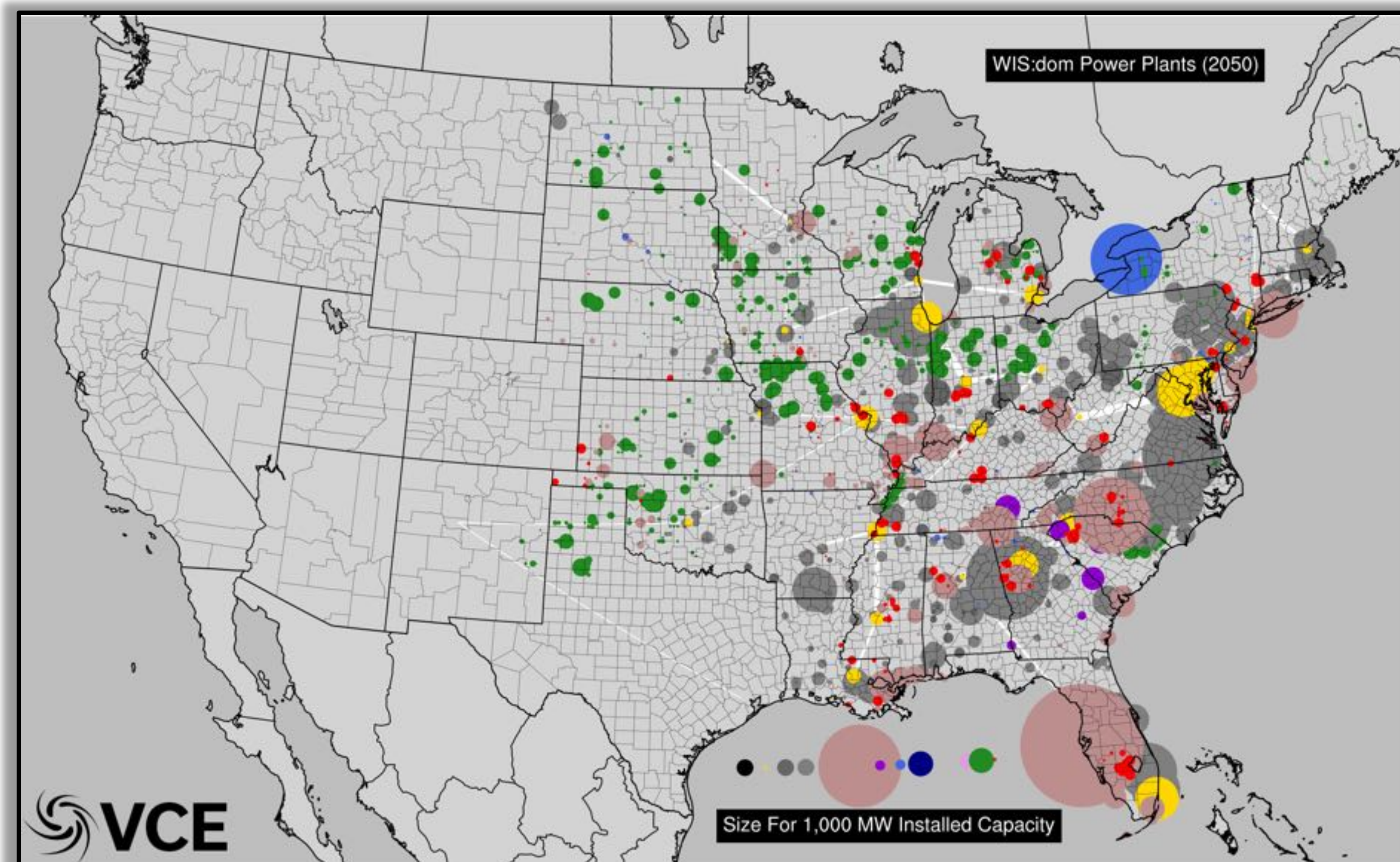


Installed Capacities



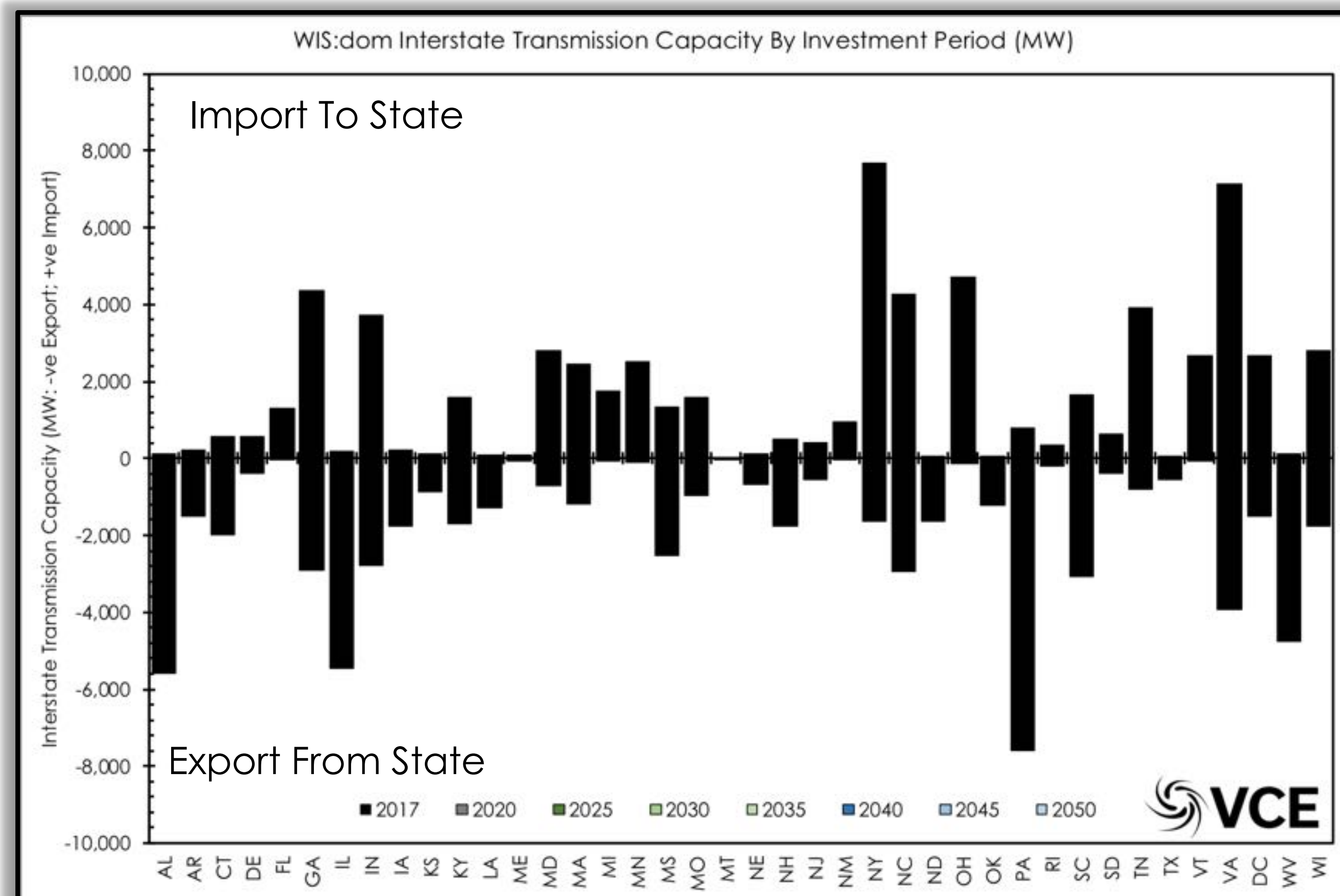
VCE VIBRANT CLEAN ENERGY

Installed Capacities

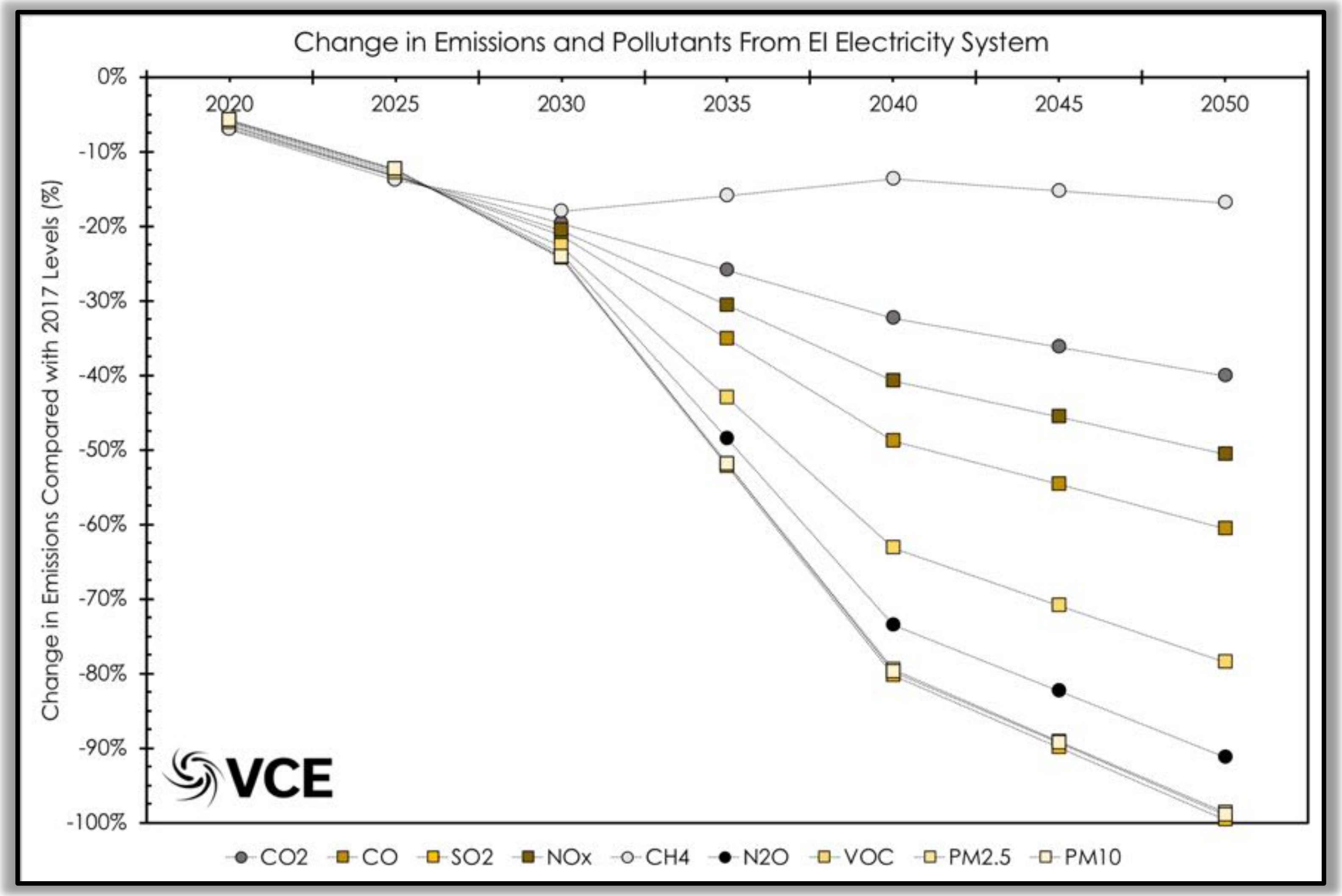


VCE
VIBRANT CLEAN ENERGY

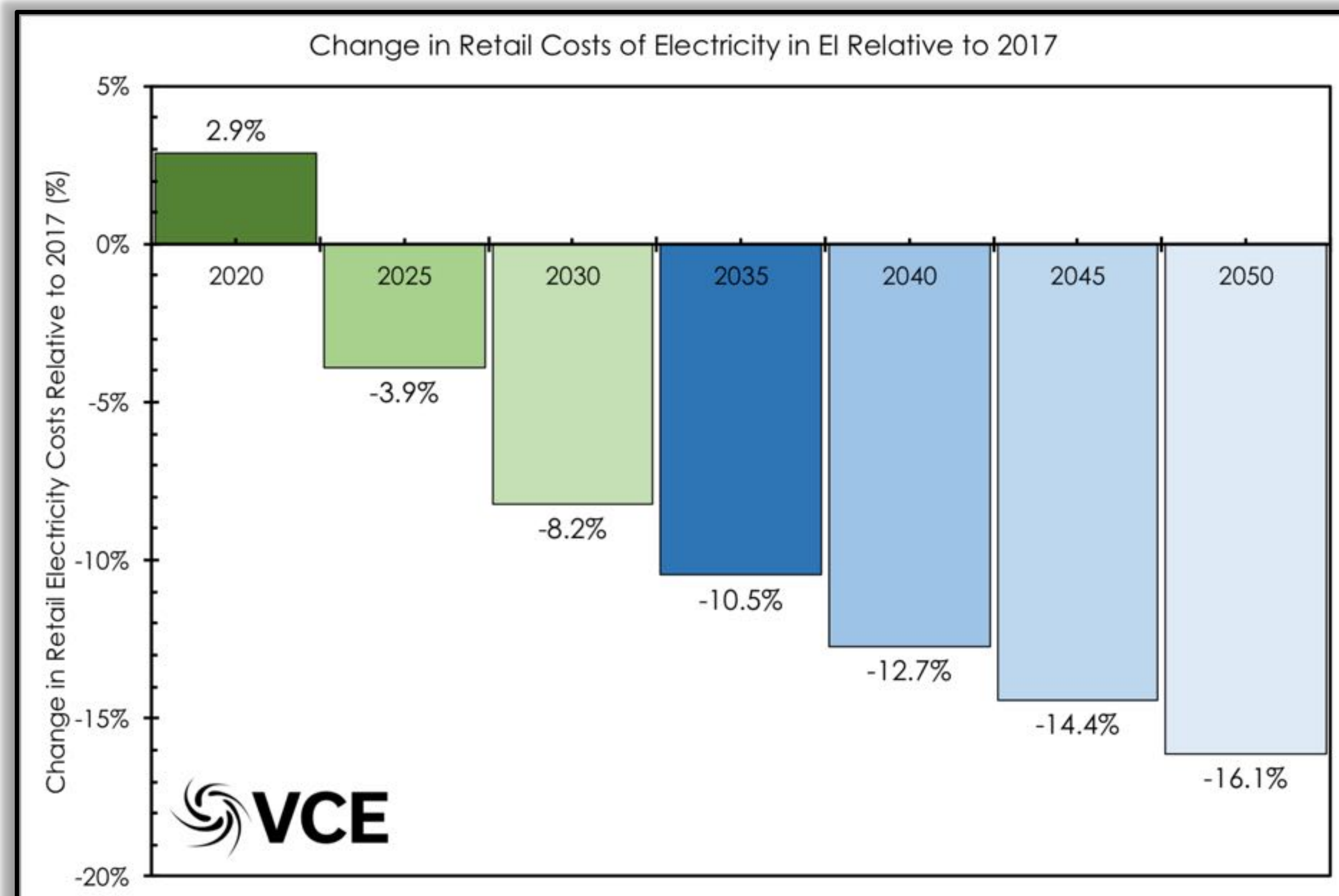
Installed Transmission Capacities



Changes in Emissions & Pollutants



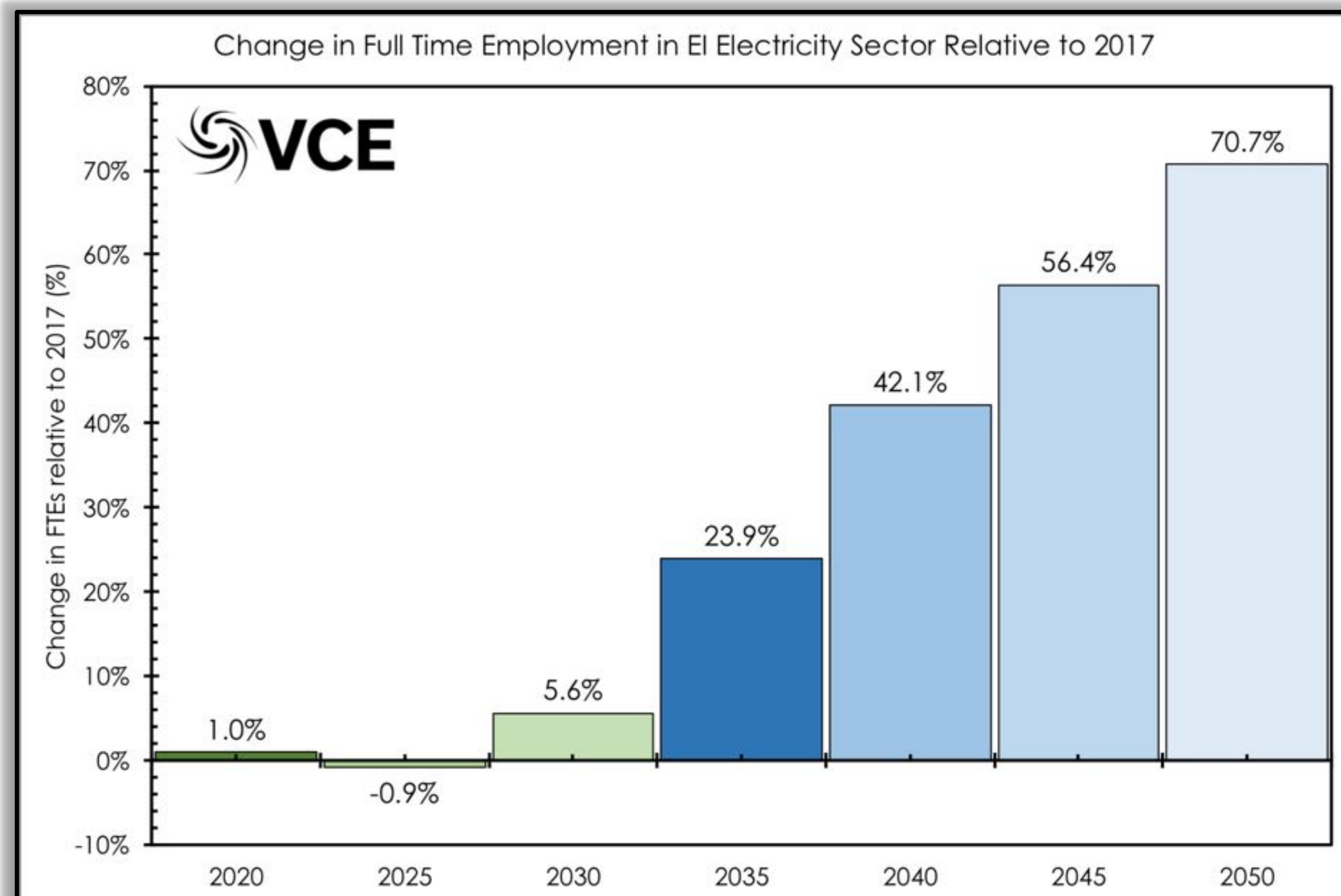
Cost Changes Compared with 2017



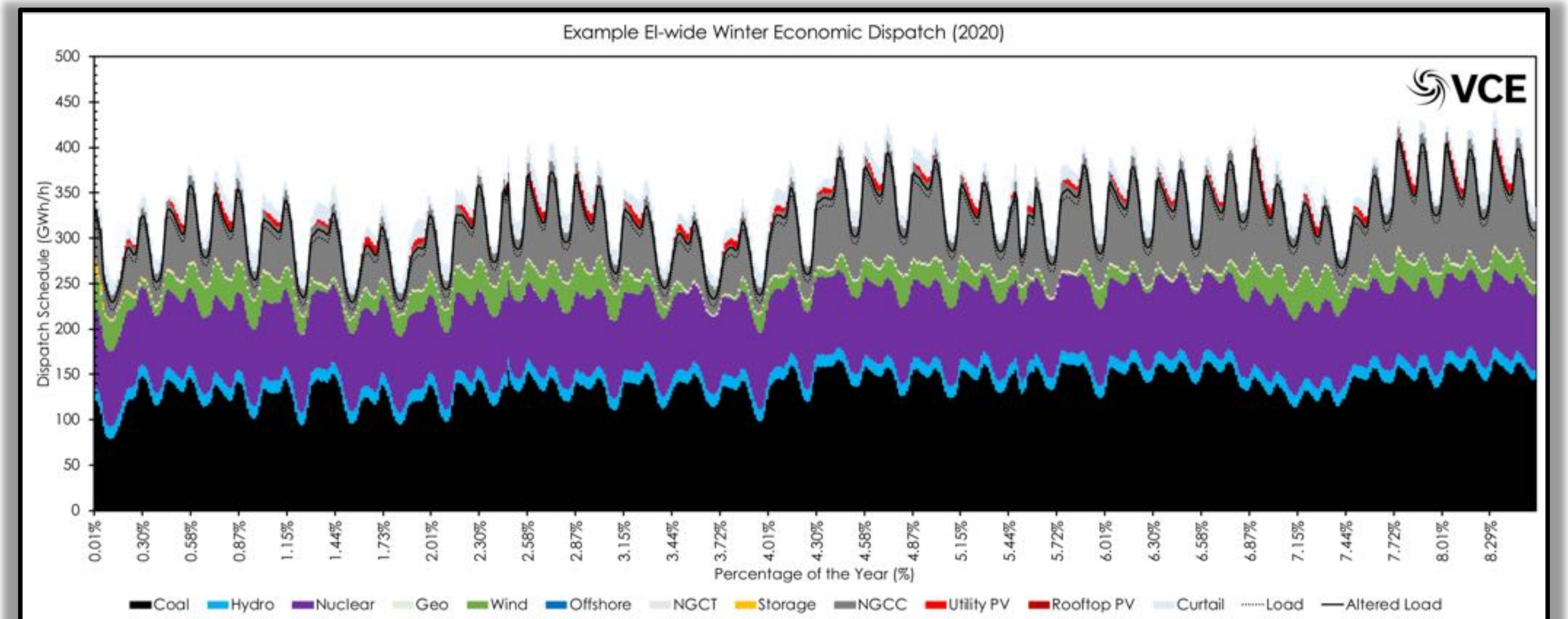
info@vibrantcleanenergy.com

VIBRANT CLEAN ENERGY

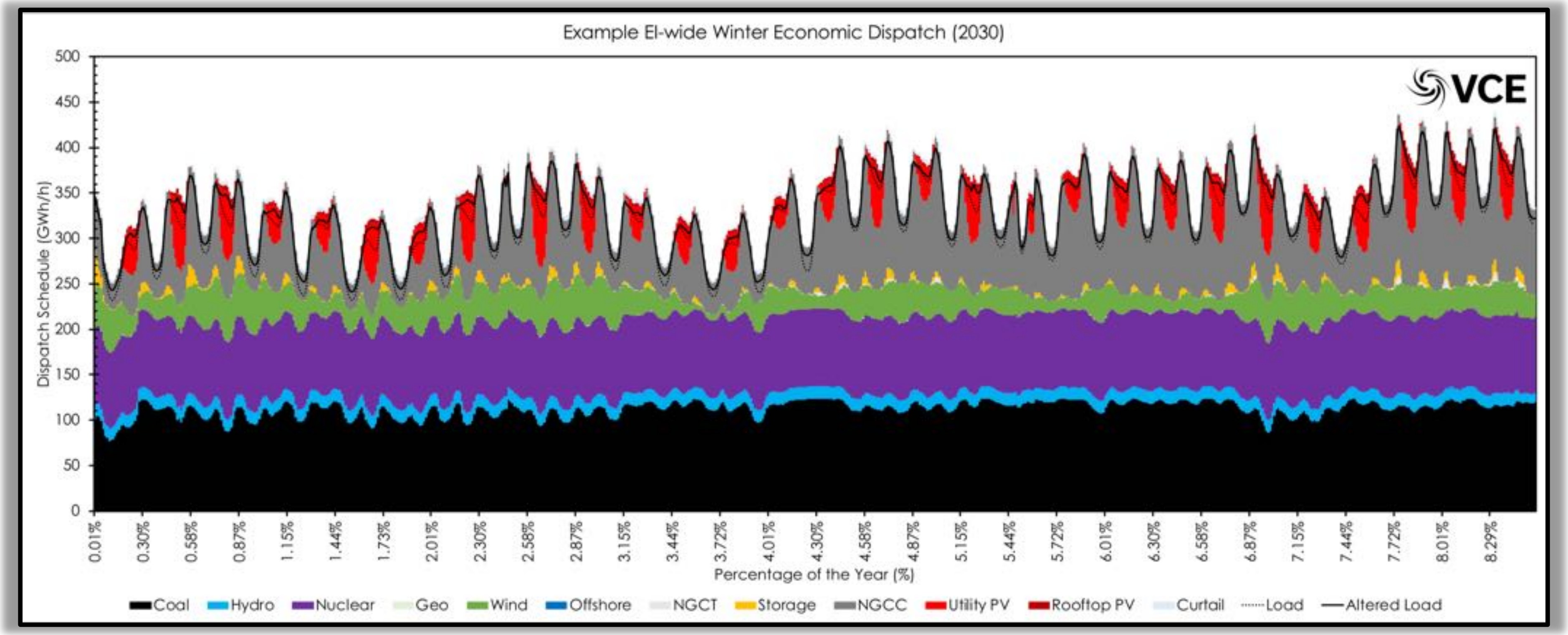
Job Changes Compared with 2017



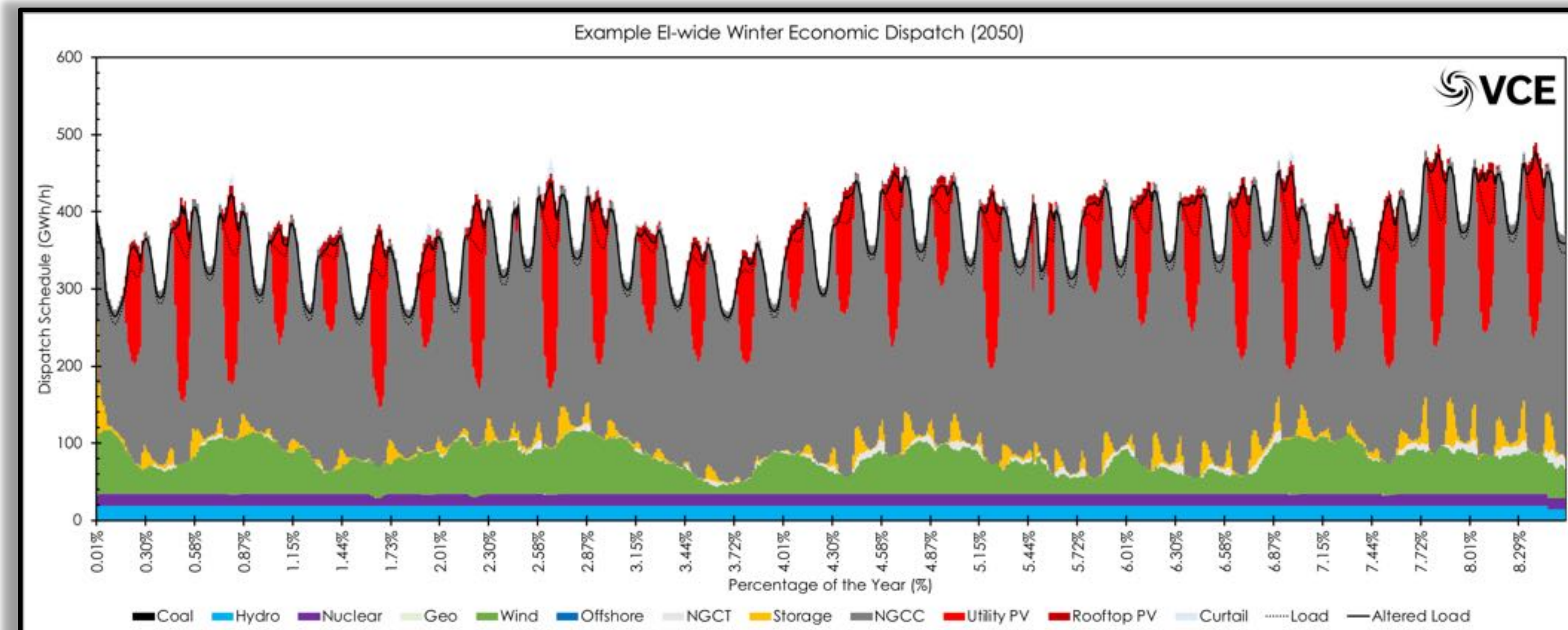
Economic Dispatch



Economic Dispatch

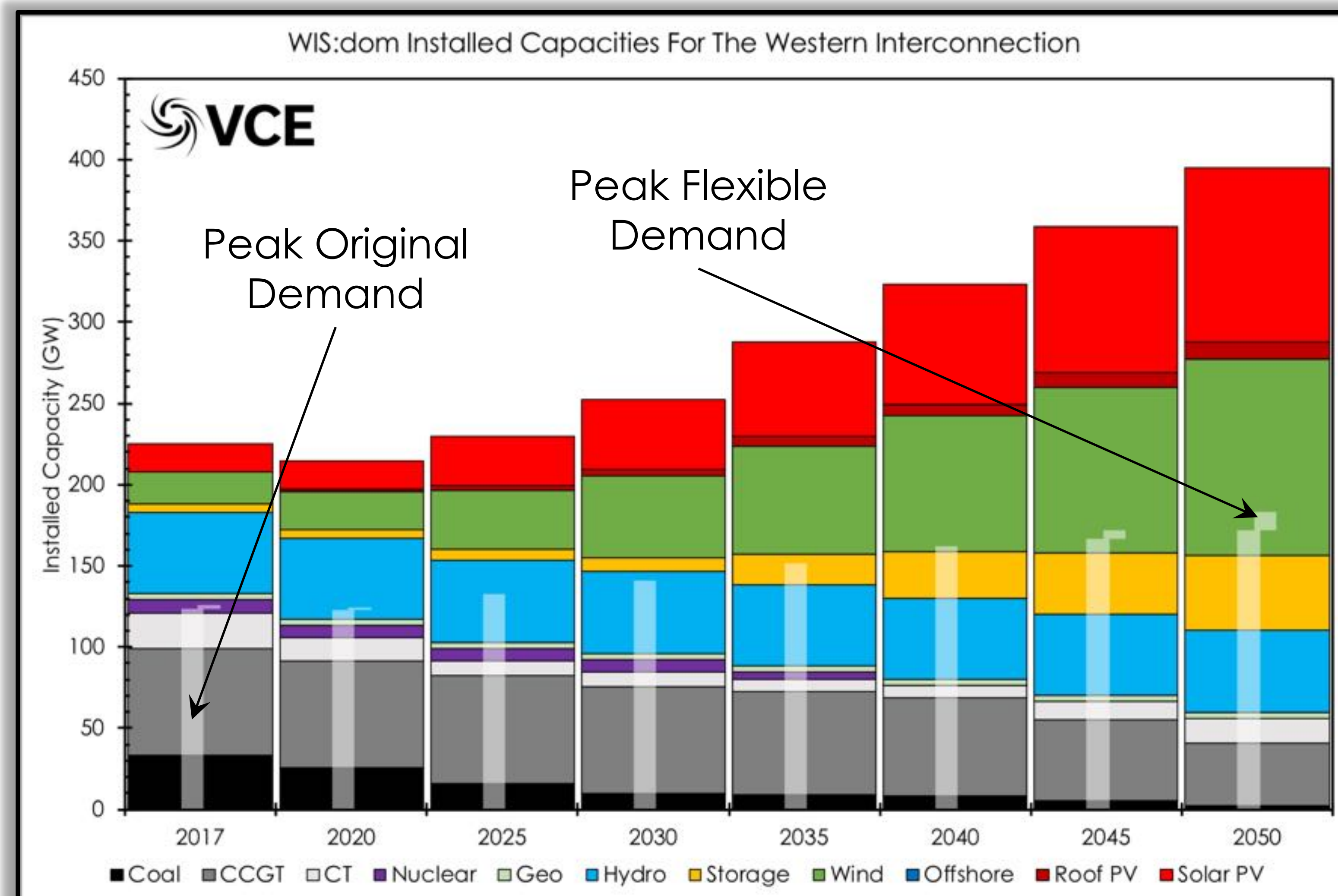


Economic Dispatch

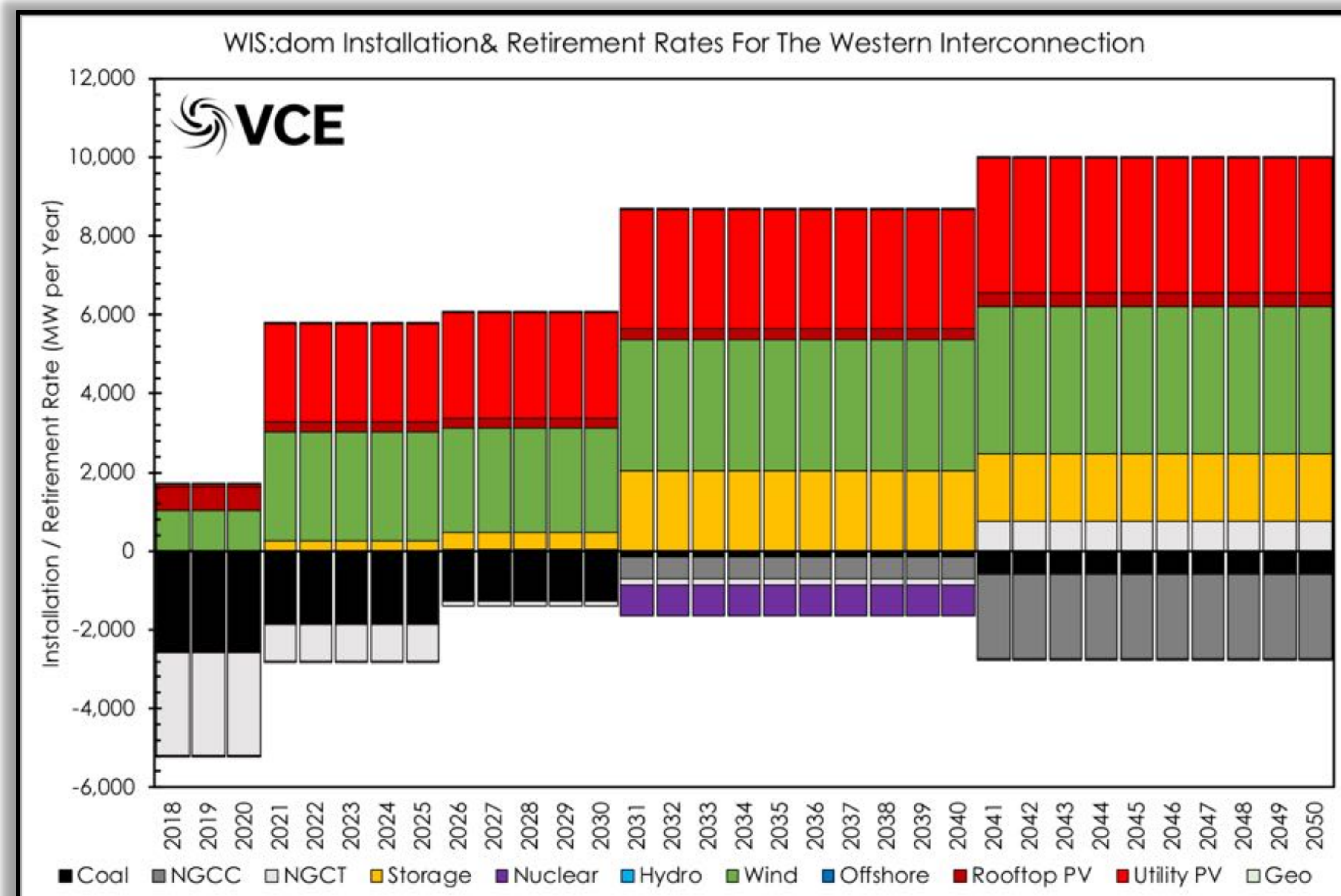


Example:
Western Interconnection Study

Installed Capacities

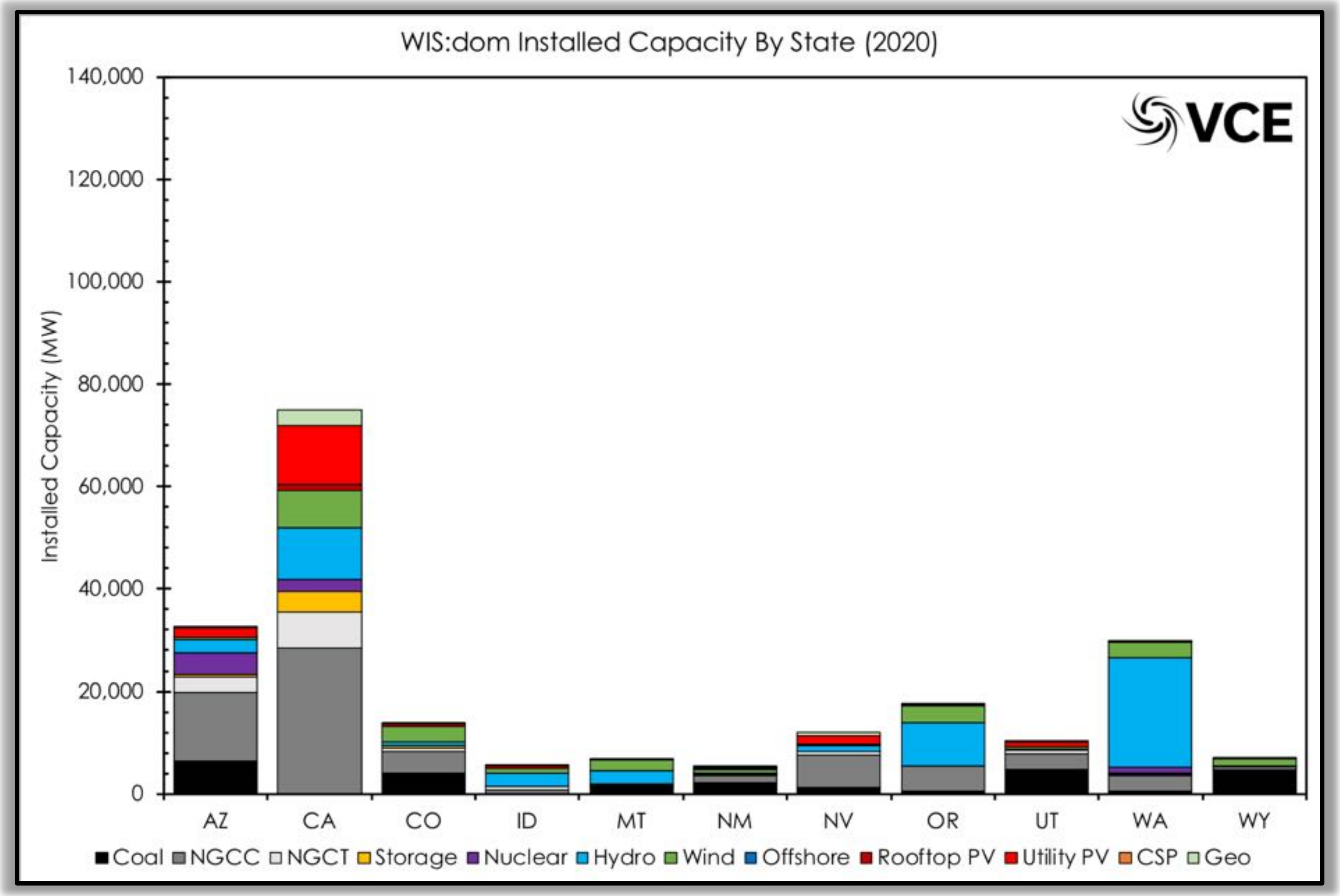


Rate Of Installations & Retirements

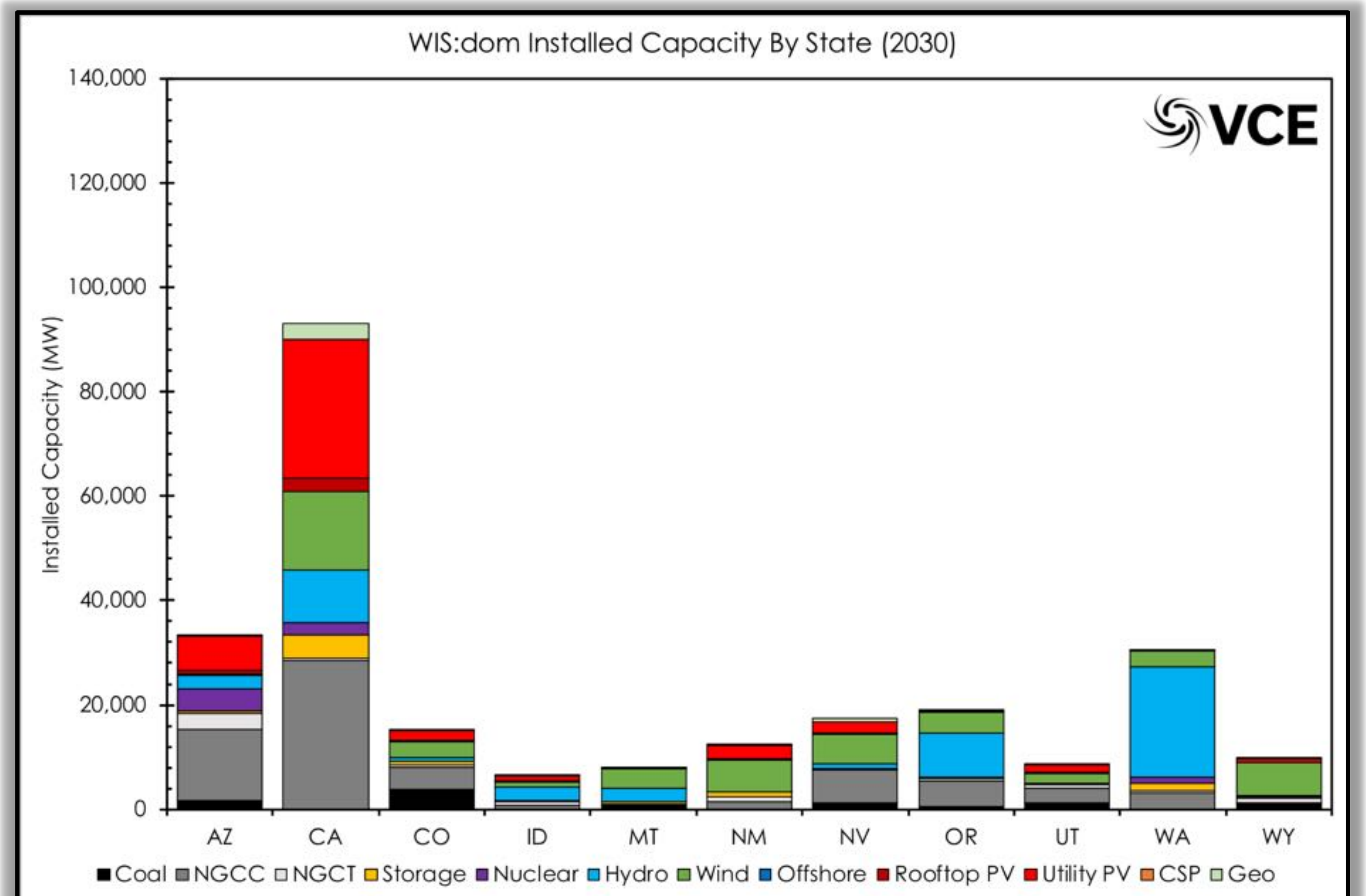


- The rate of installations increases with time. Coal retirements are rapid at first and then slow, before natural gas retirements dominate.

Installed Capacities

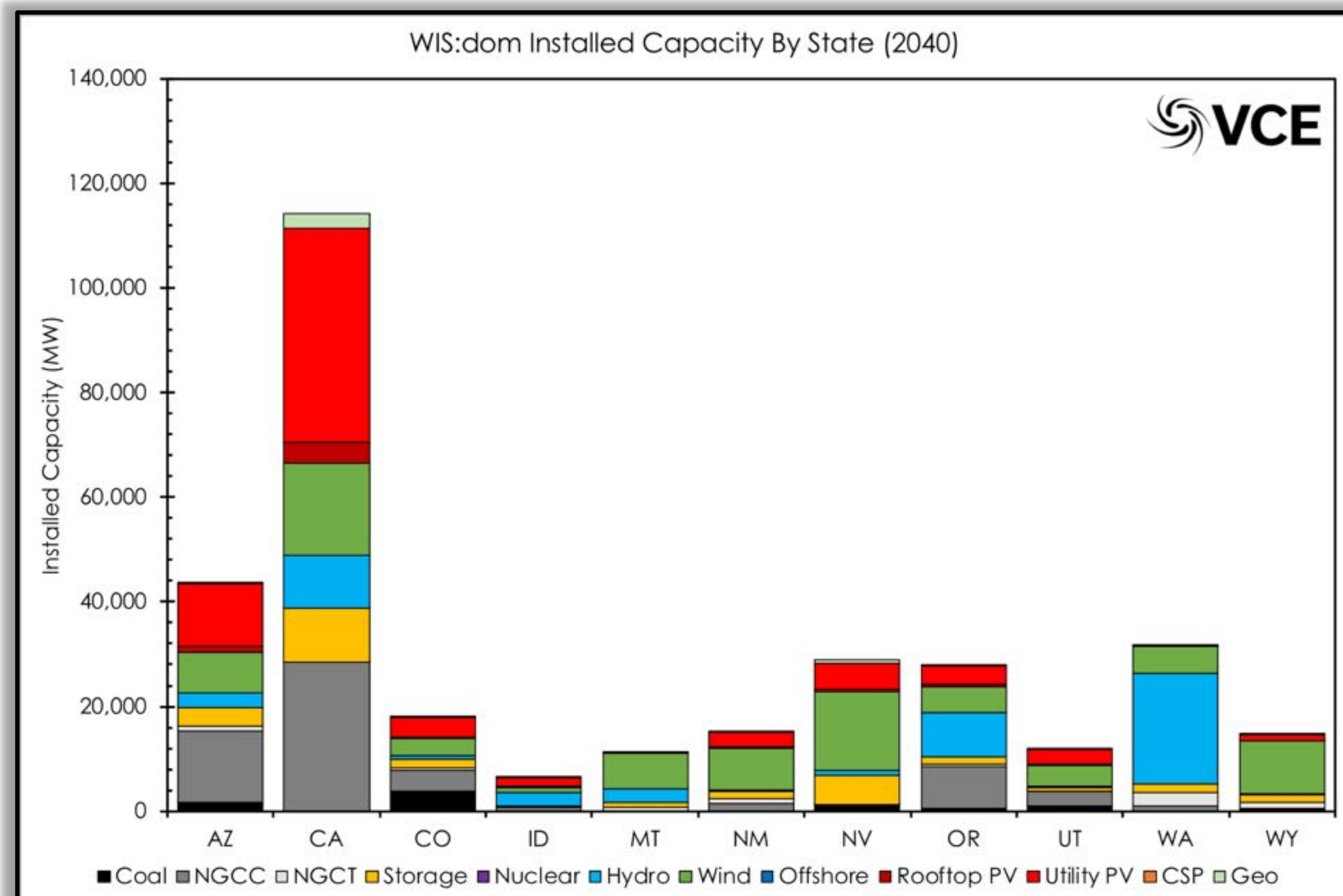


Installed Capacities

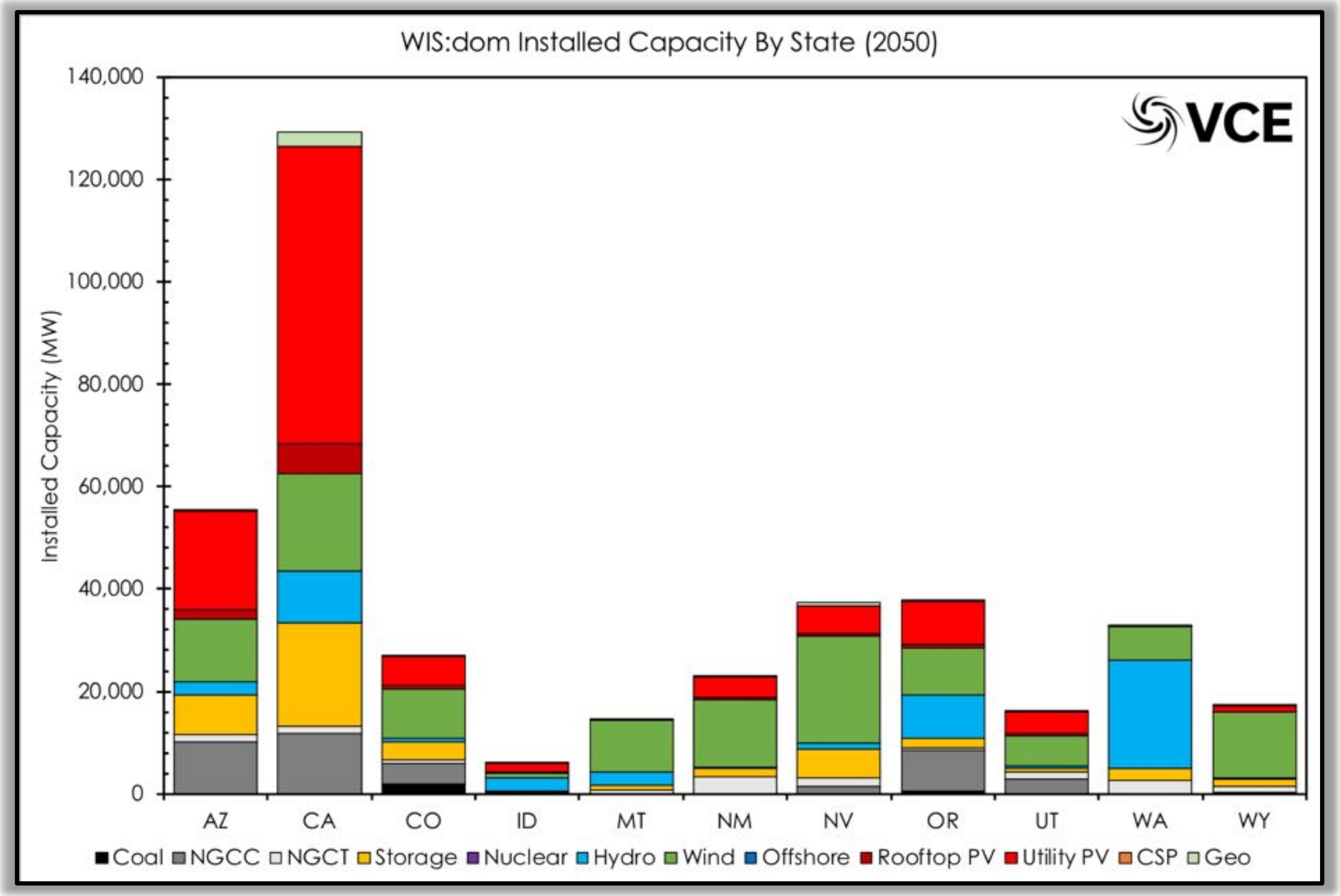


info@vibrantcleanenergy.com

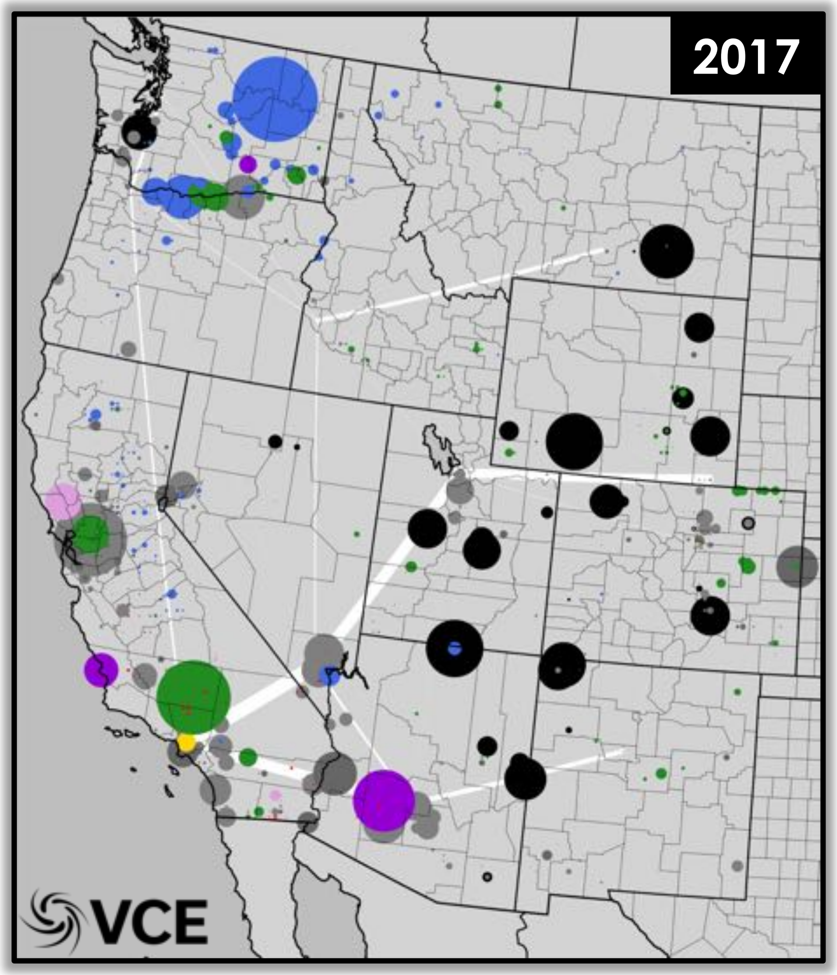
Installed Capacities

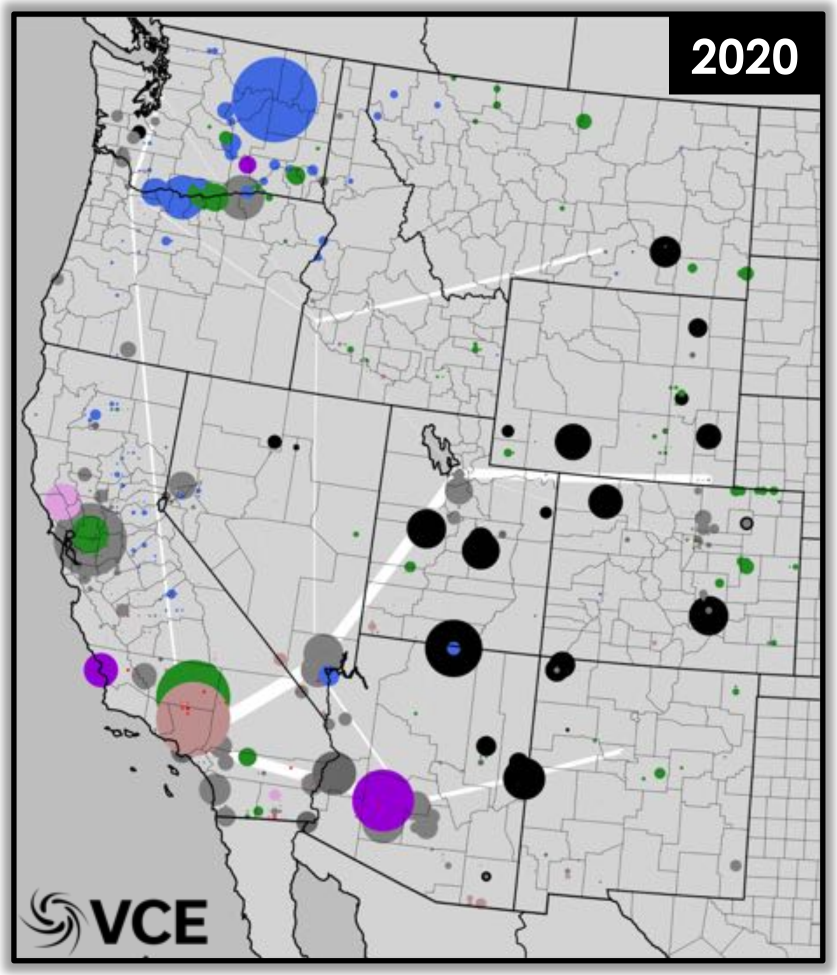


Installed Capacities



Installed Capacities

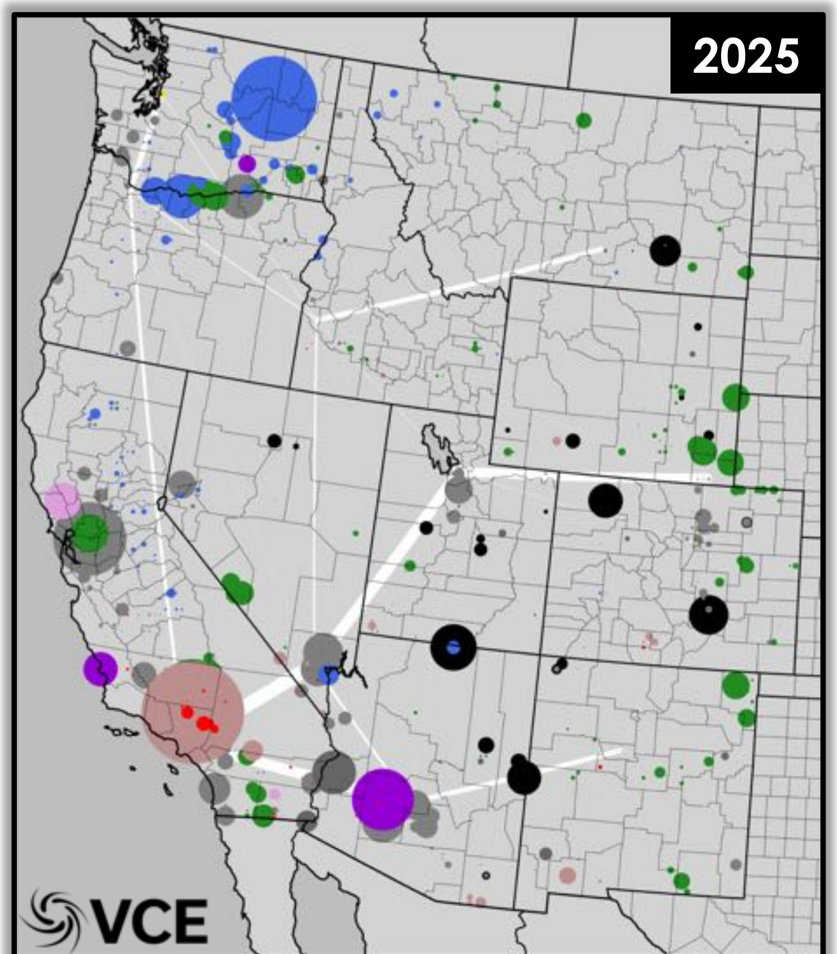


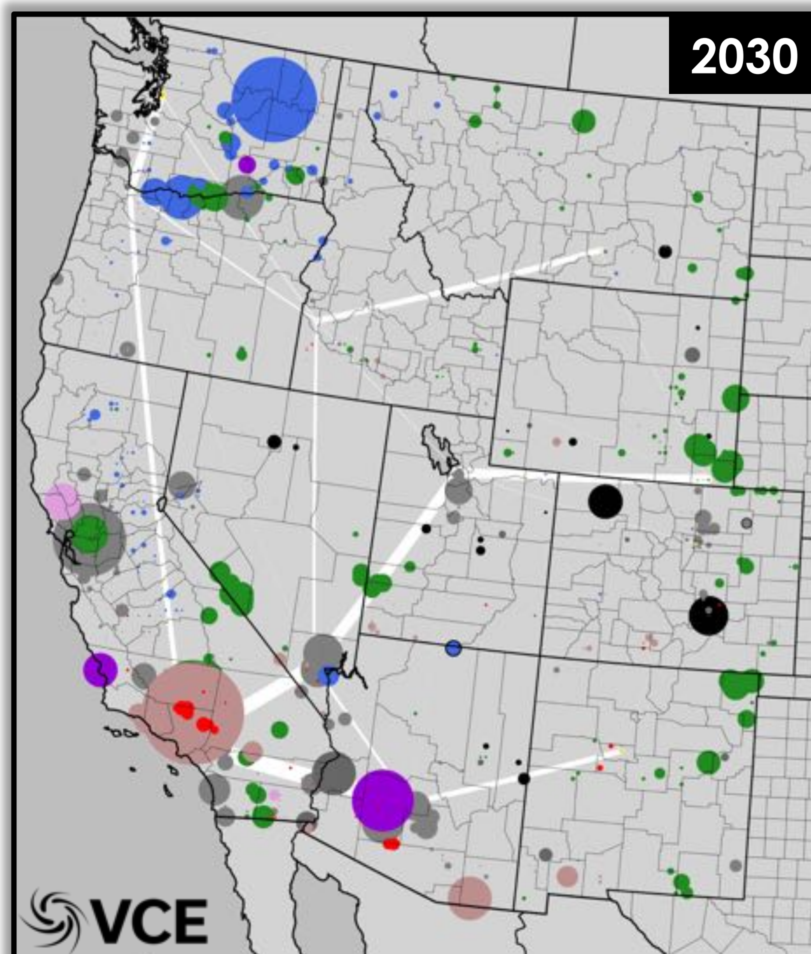


- Interstate transmission capacity is shown in white. Black is coal plants, grey is natural gas, green is wind, red is solar, purple is nuclear, blue is hydroelectric and purple is nuclear.

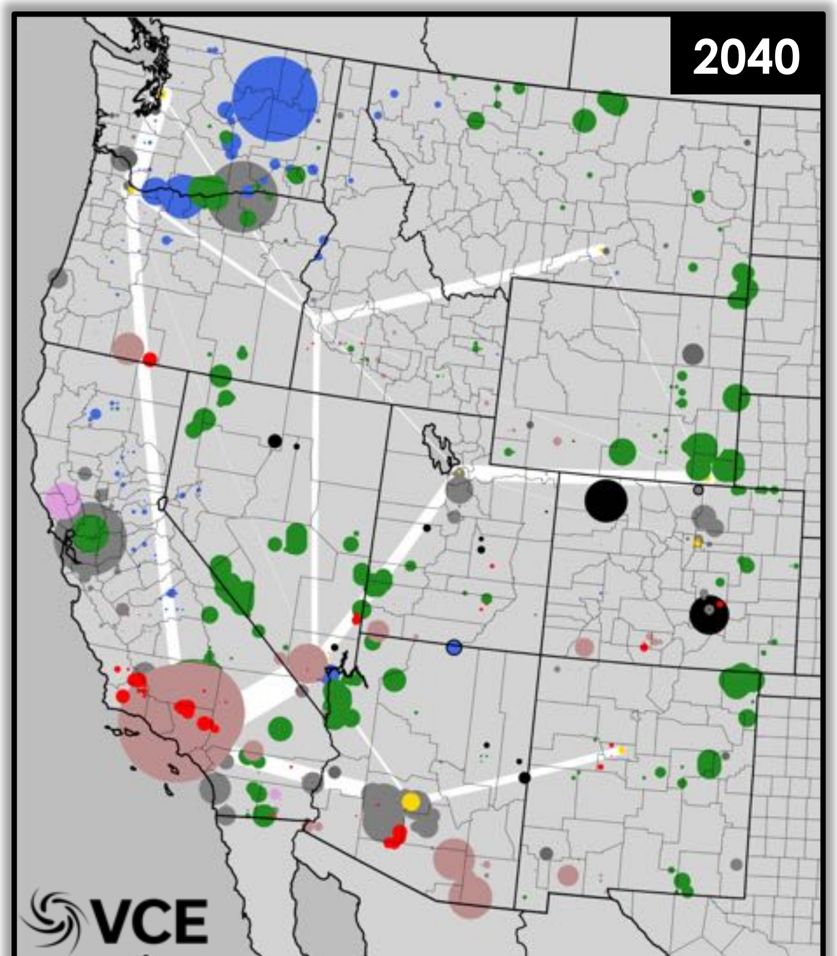
info@vibrantcleanenergy.com

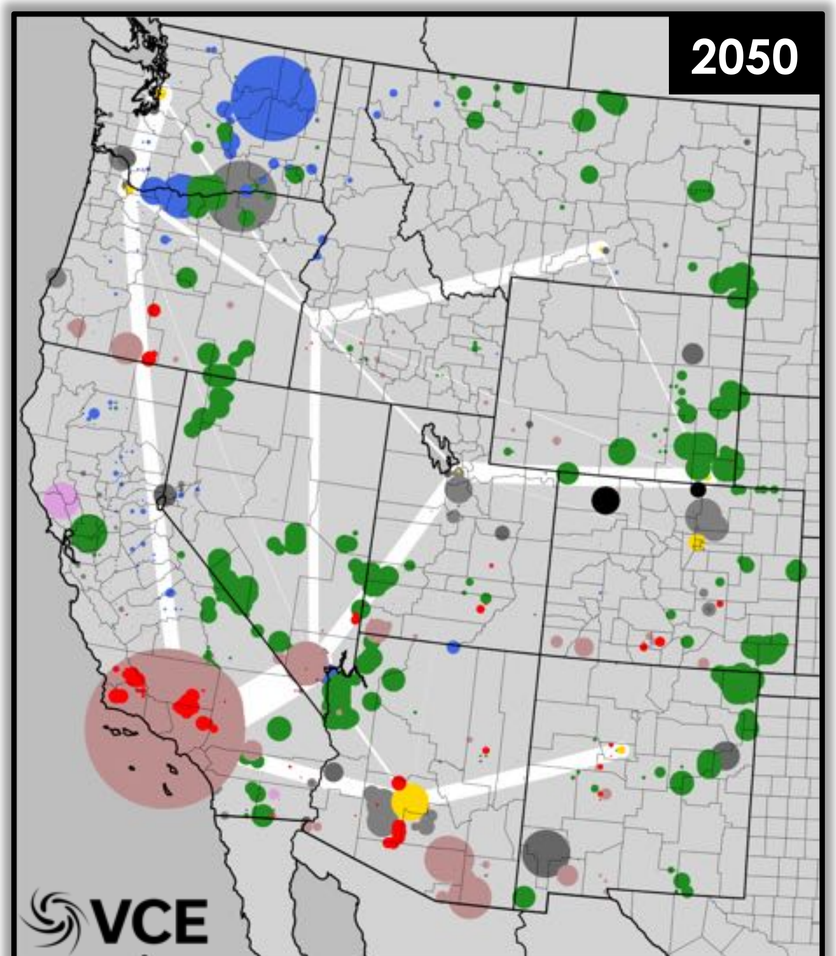
Installed Capacities





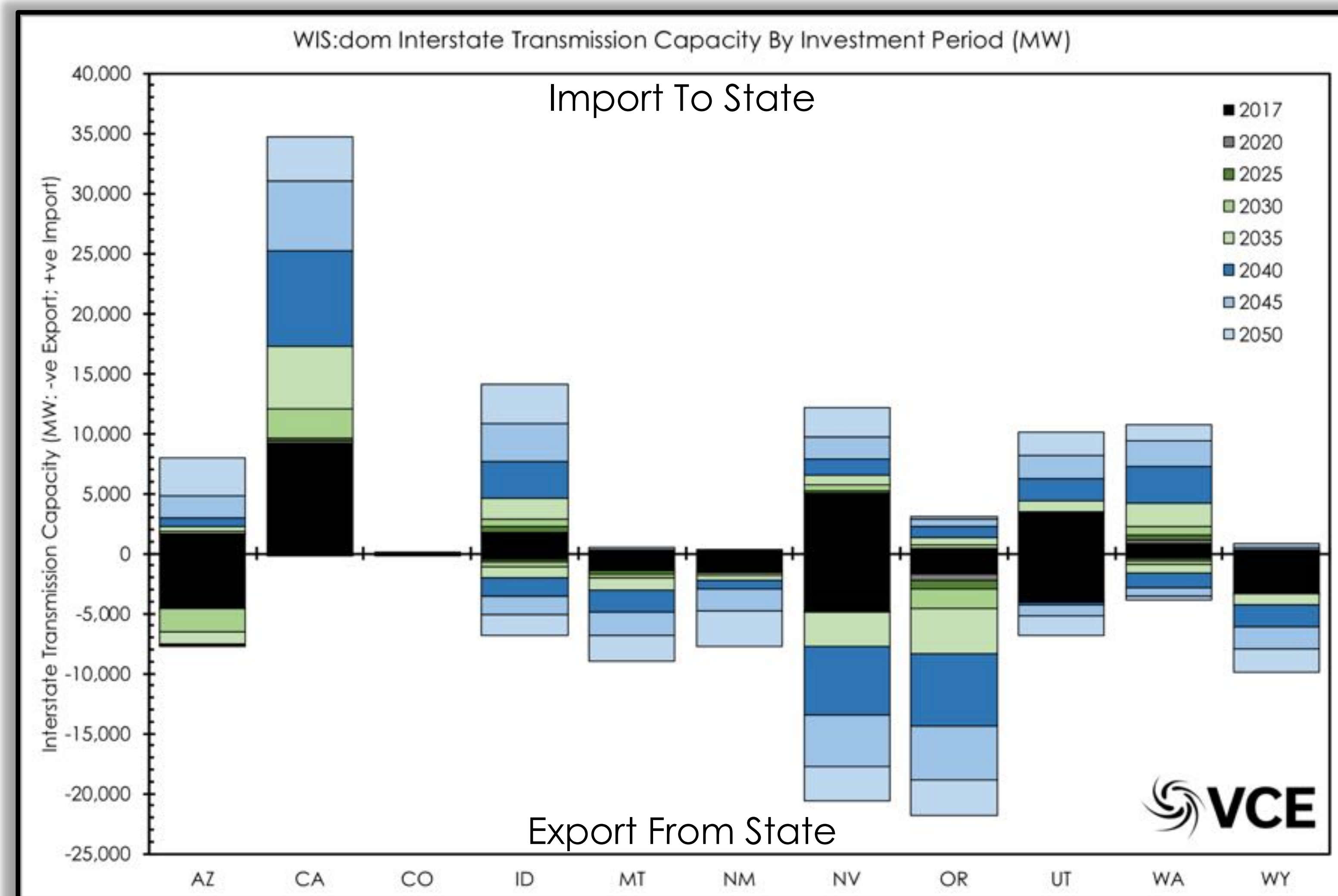
Installed Capacities





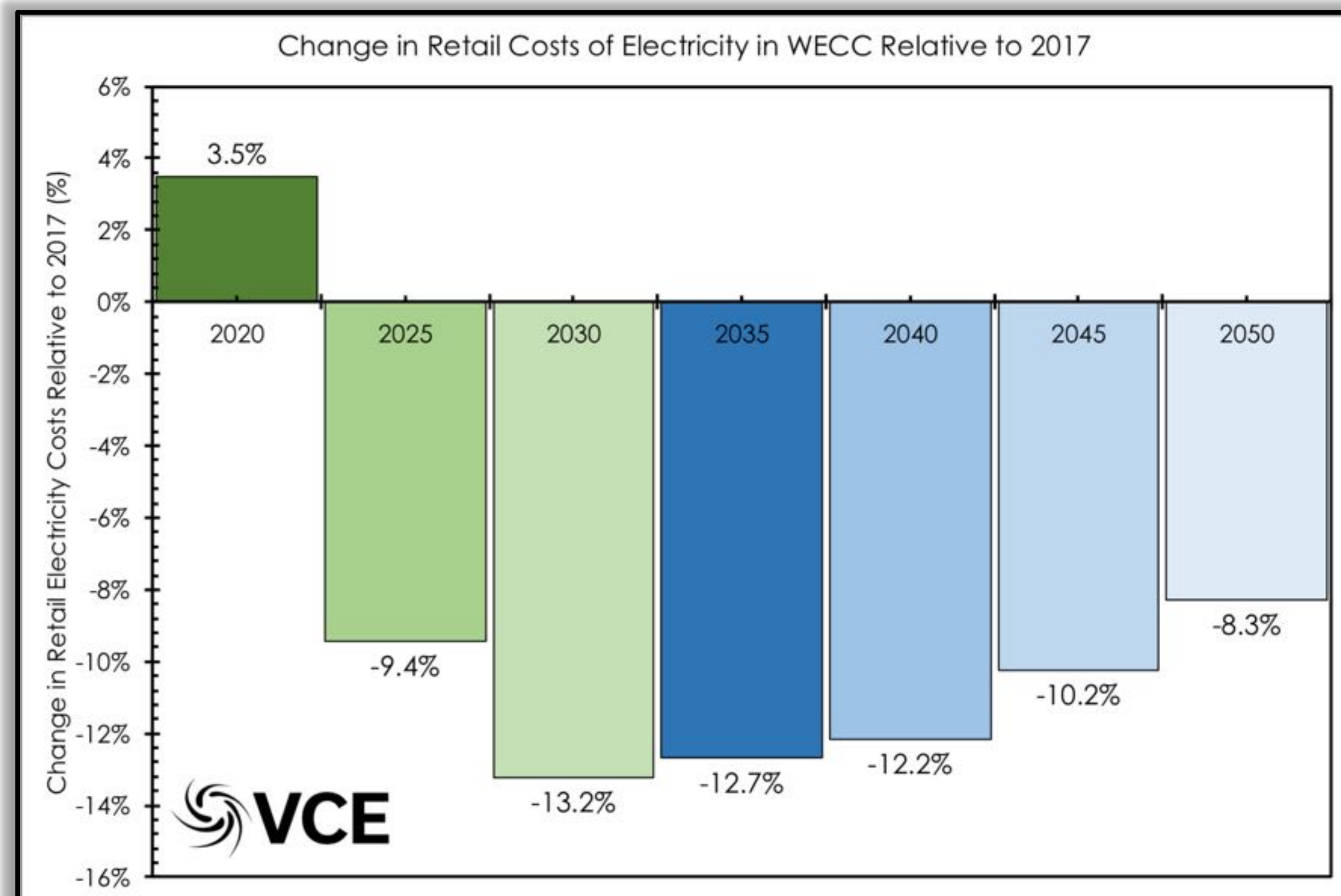
VCE VIBRANT CLEAN ENERGY

Installed Transmission Capacities



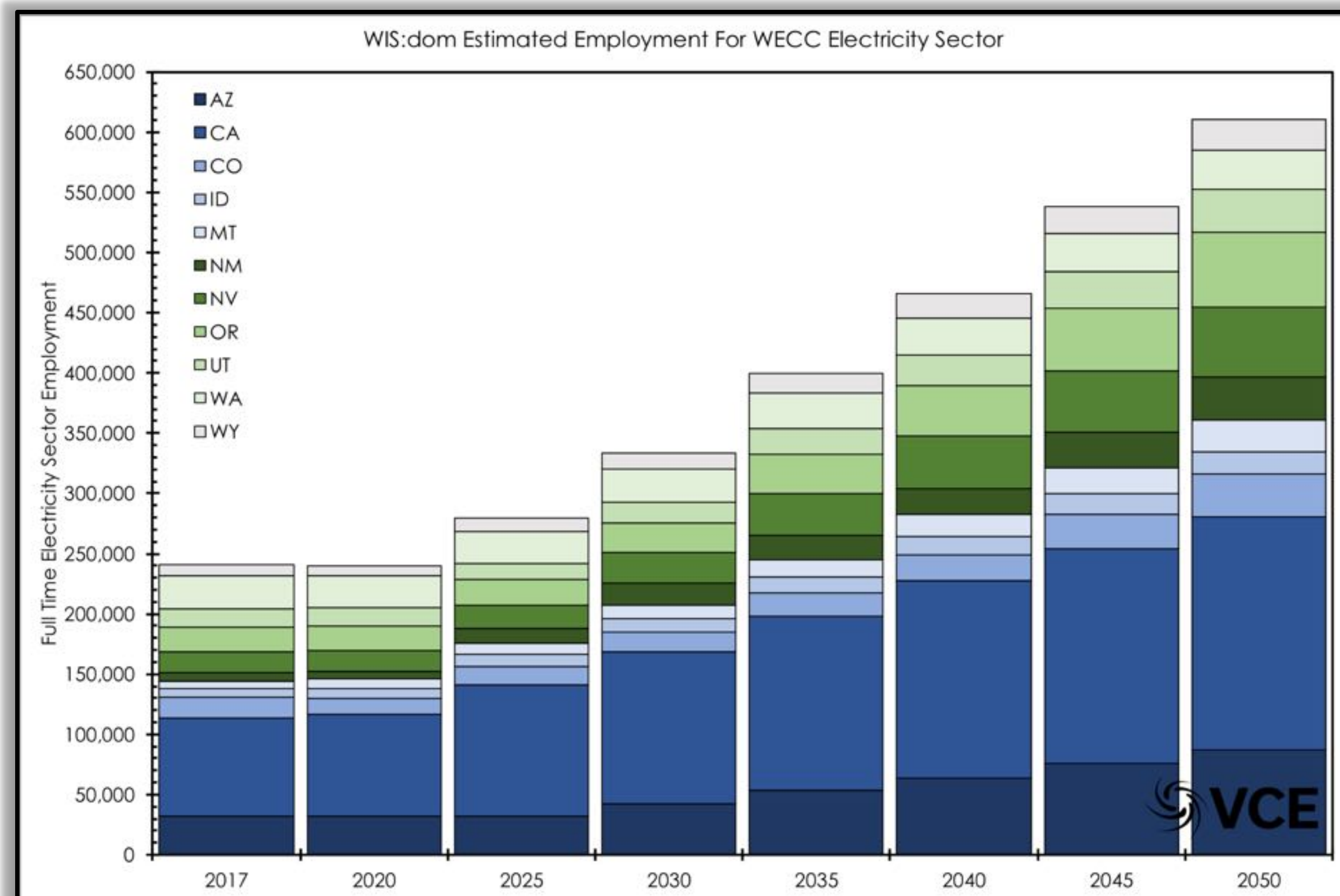
VCE VIBRANT CLEAN ENERGY

LCOE Changes Compared with 2017



- In the very near-term electricity costs rise a small amount, and then fall substantially.

Full-time Jobs In Electricity Over WECC

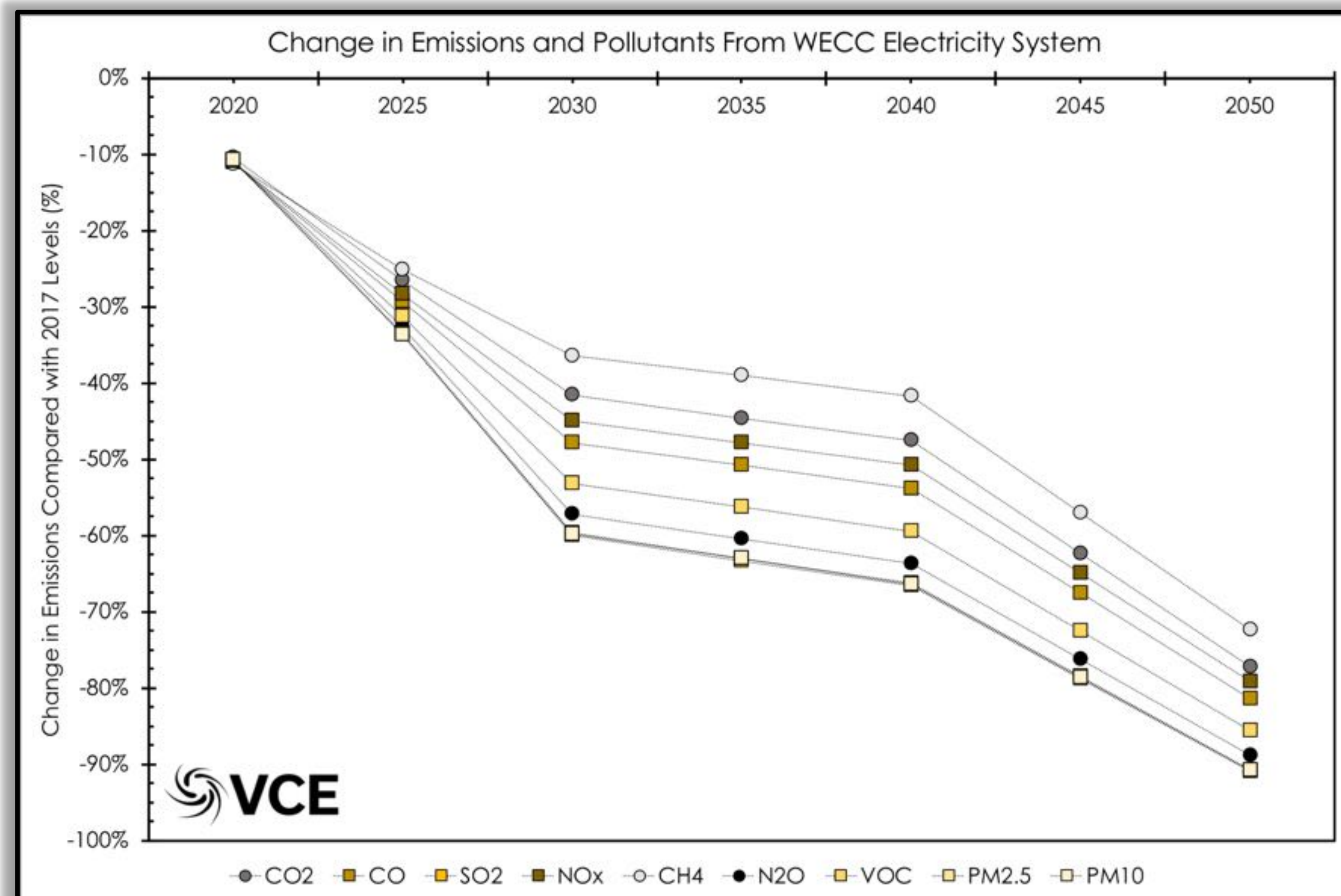


- Under baseline conditions, there are 61% more full time jobs in the electricity sector compared with 2017 numbers.

info@vibrantcleanenergy.com

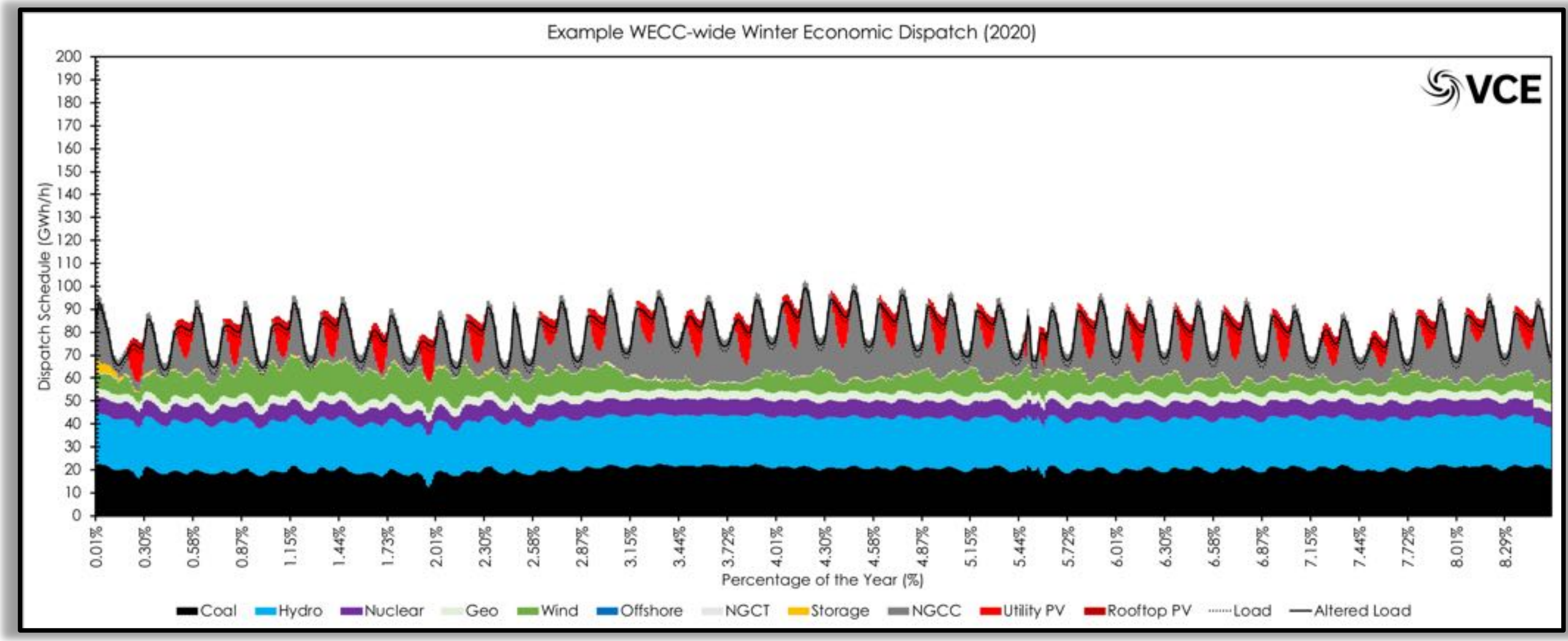
VIBRANT CLEAN ENERGY

Changes in Emissions & Pollutants



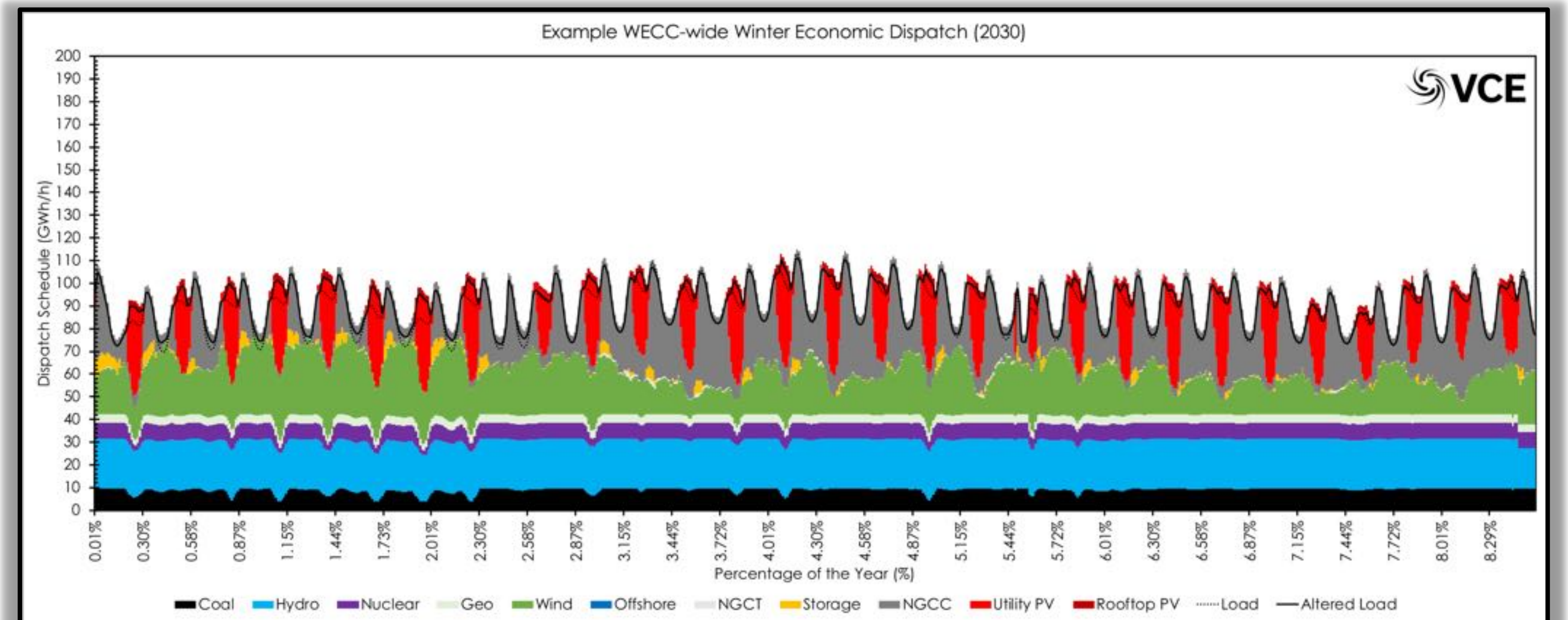
- Reductions driven by transitioning from coal to gas, as well as RPS levels being reached across the WECC footprint are substantial by 2050.

WECC-wide Winter Dispatch

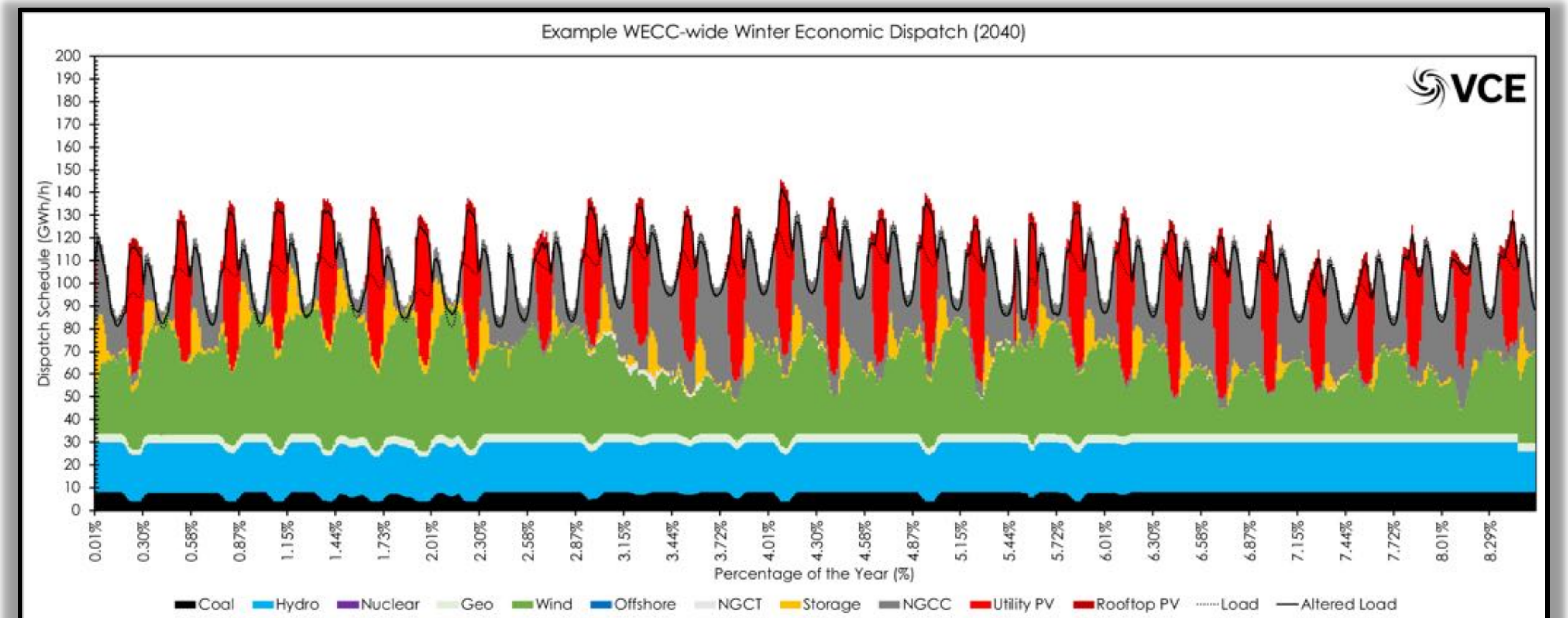


VIBRANT CLEAN ENERGY

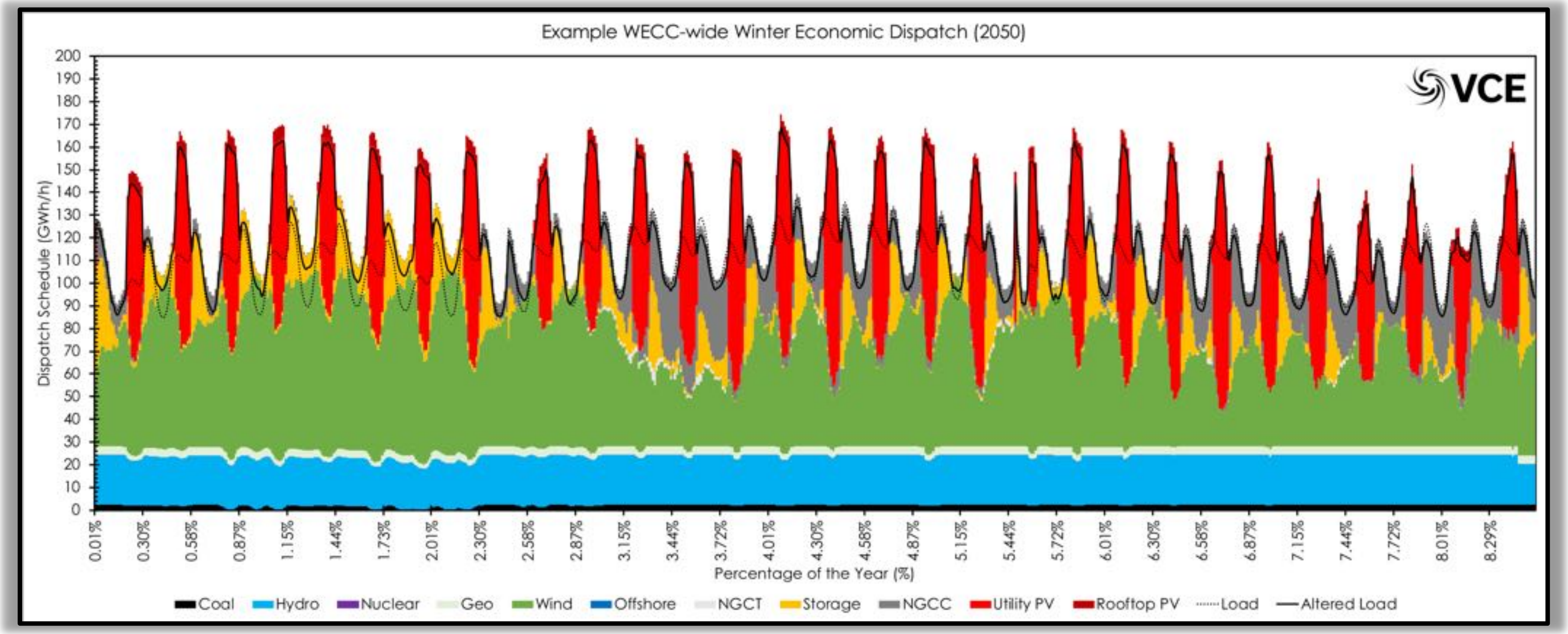
WECC-wide Winter Dispatch



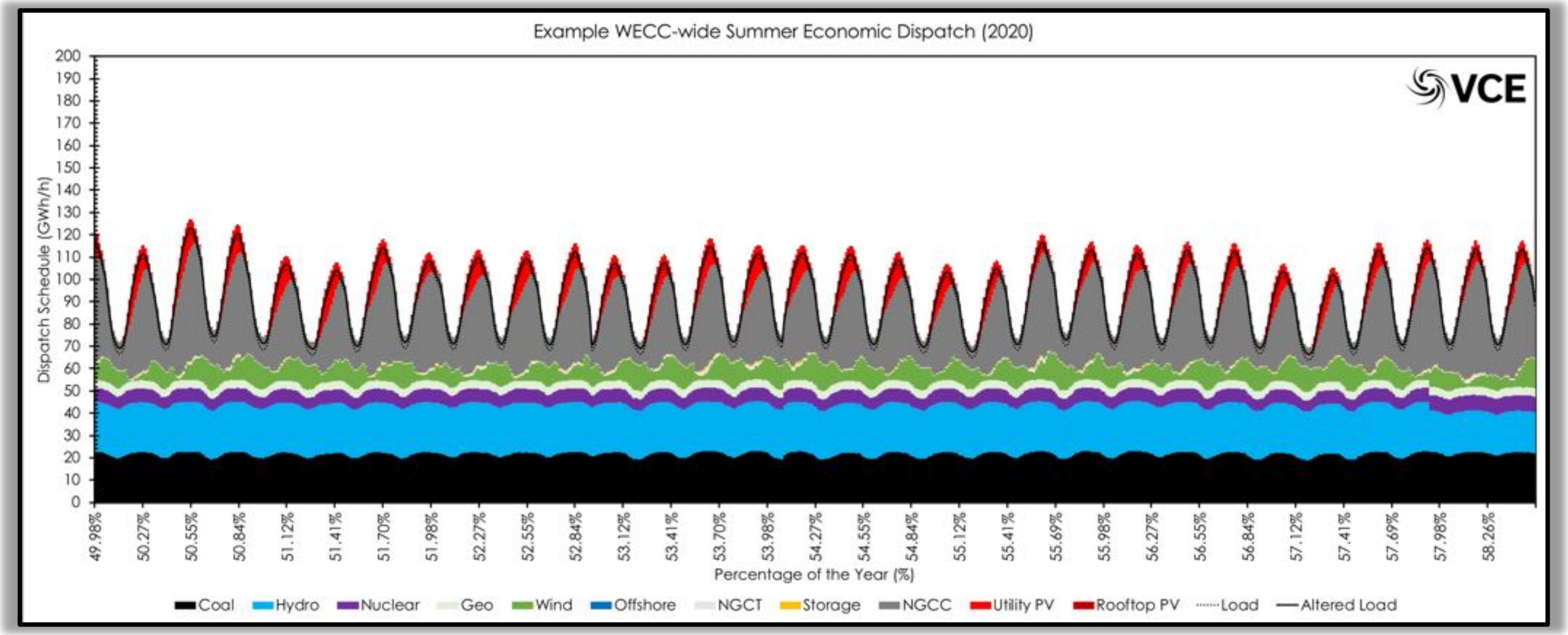
WECC-wide Winter Dispatch



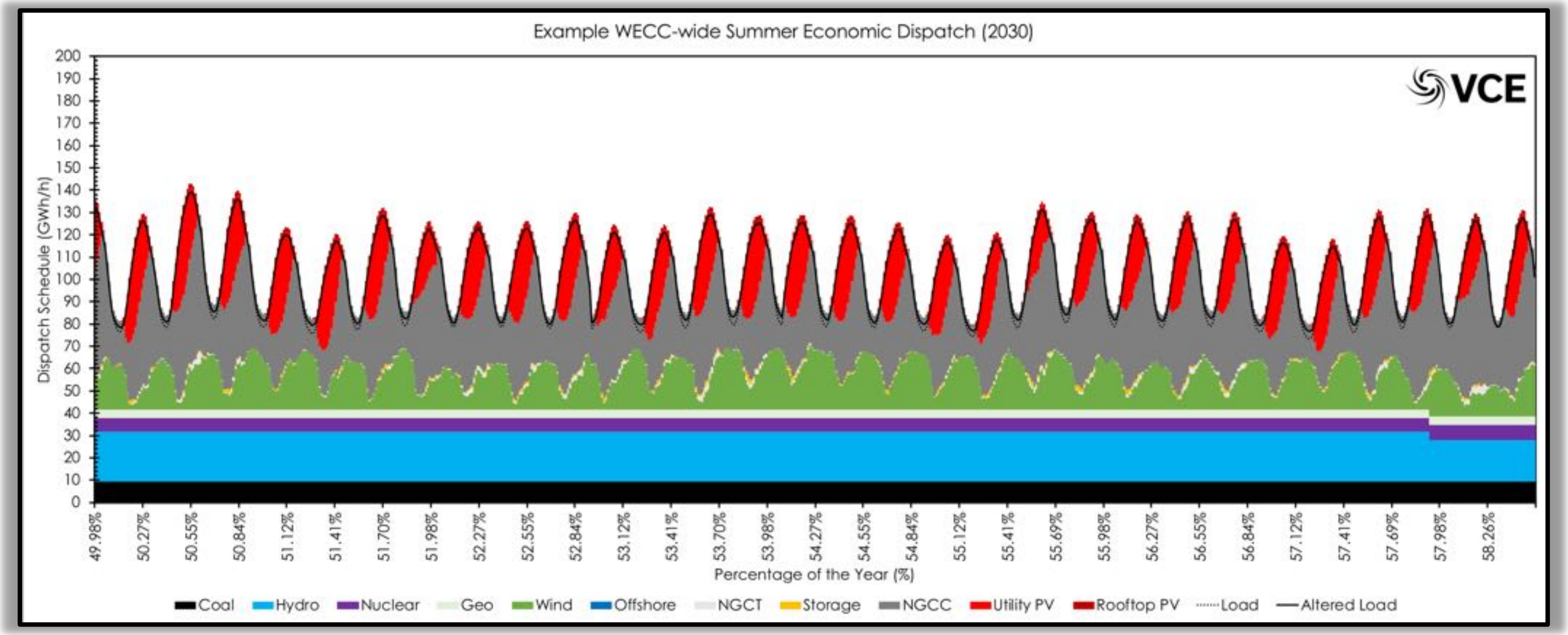
WECC-wide Winter Dispatch



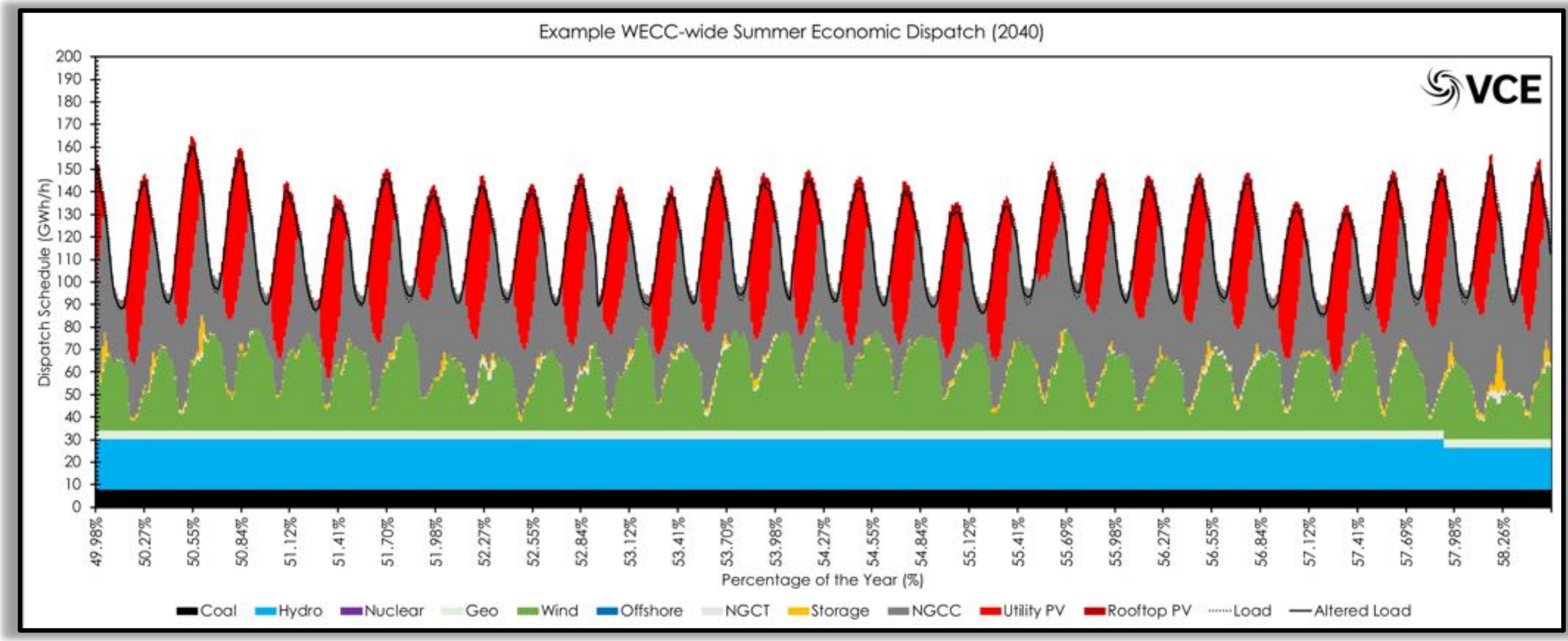
WECC-wide Summer Dispatch



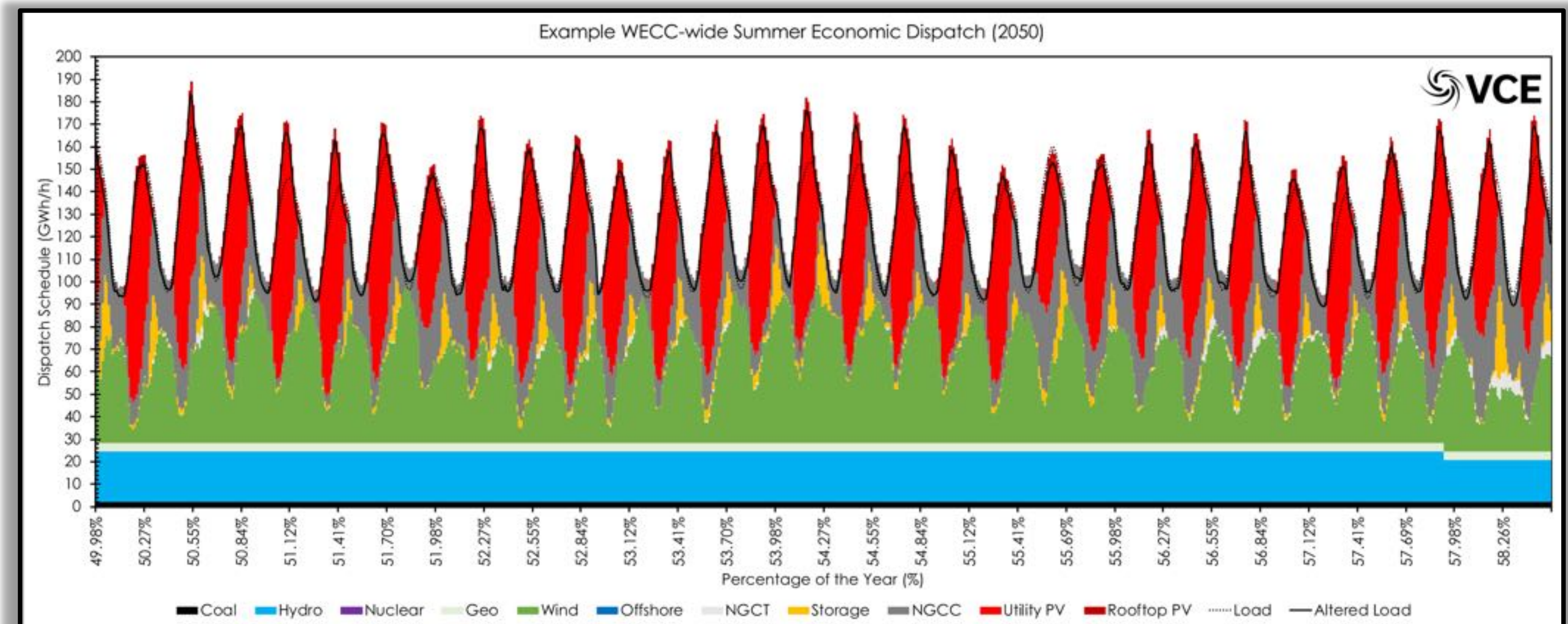
WECC-wide Summer Dispatch



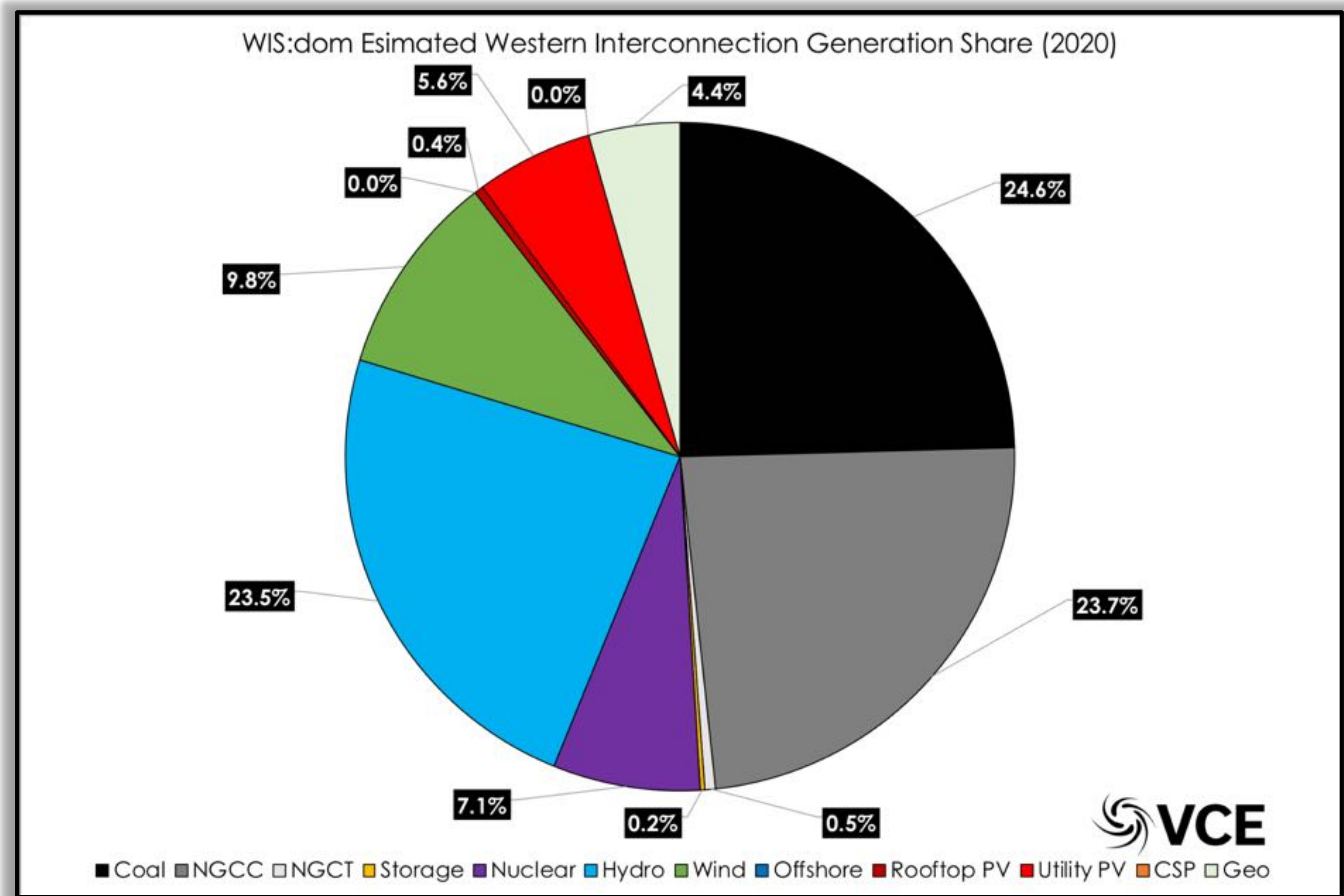
WECC-wide Summer Dispatch



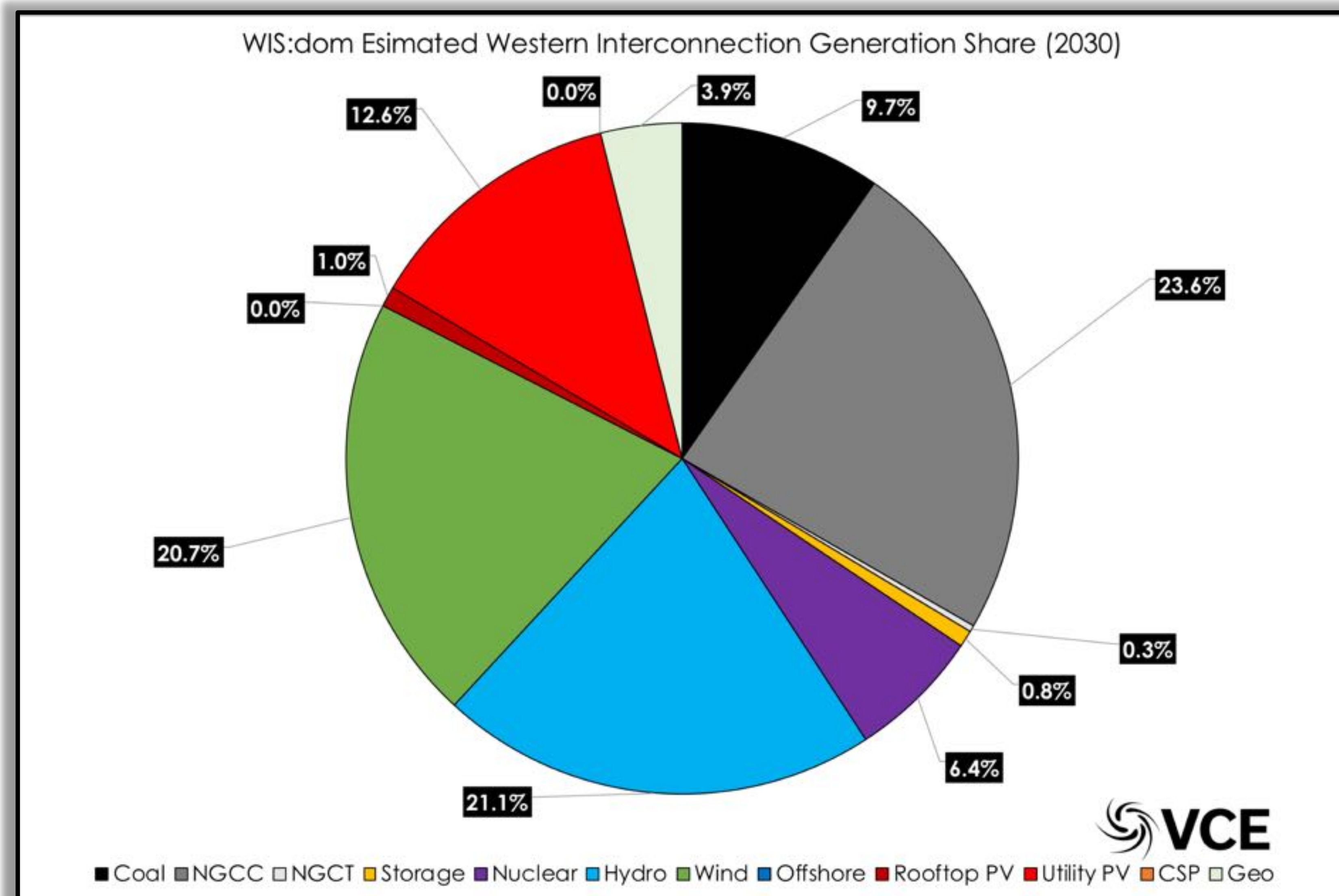
WECC-wide Summer Dispatch



WECC-wide Electricity Generation

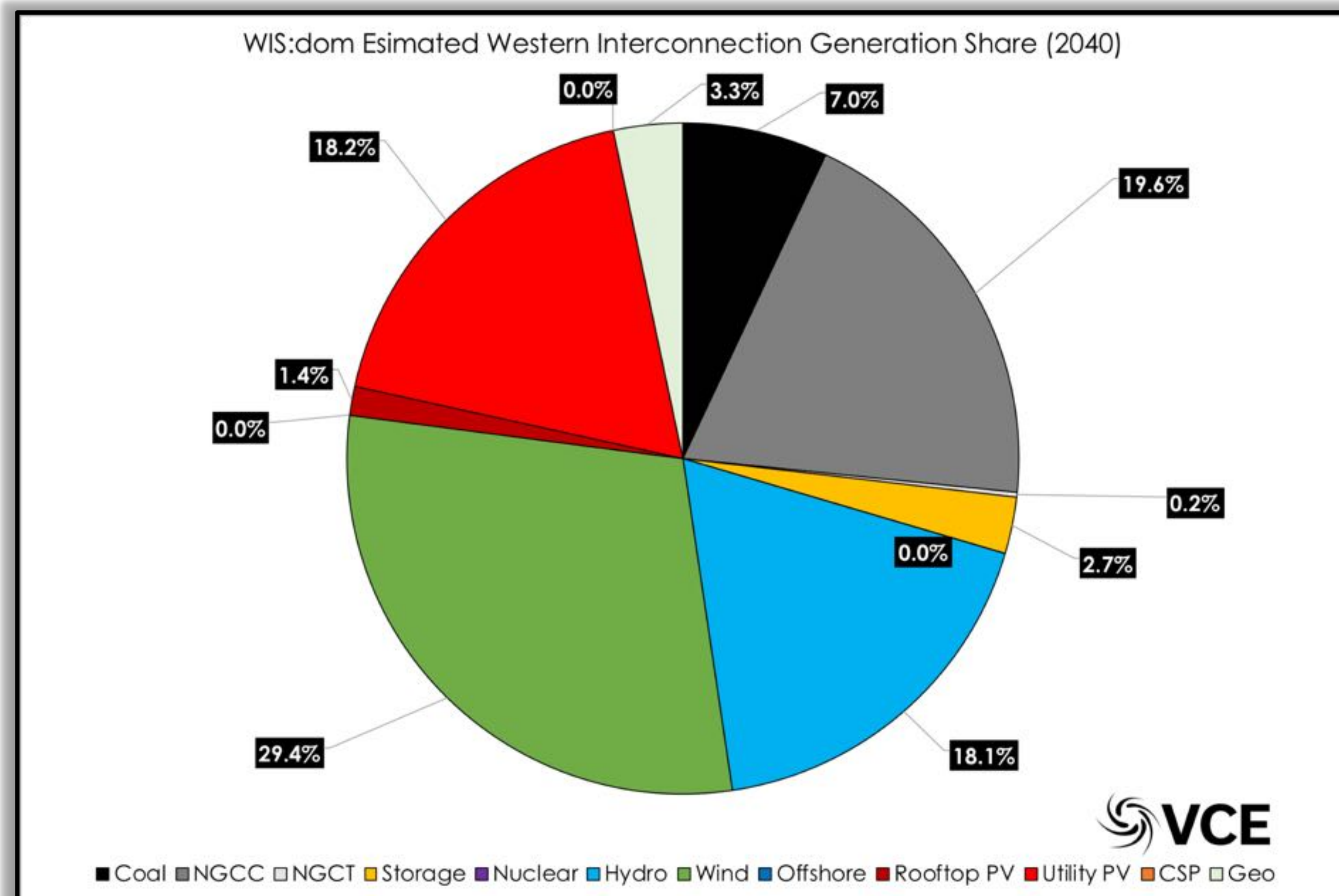


WECC-wide Electricity Generation



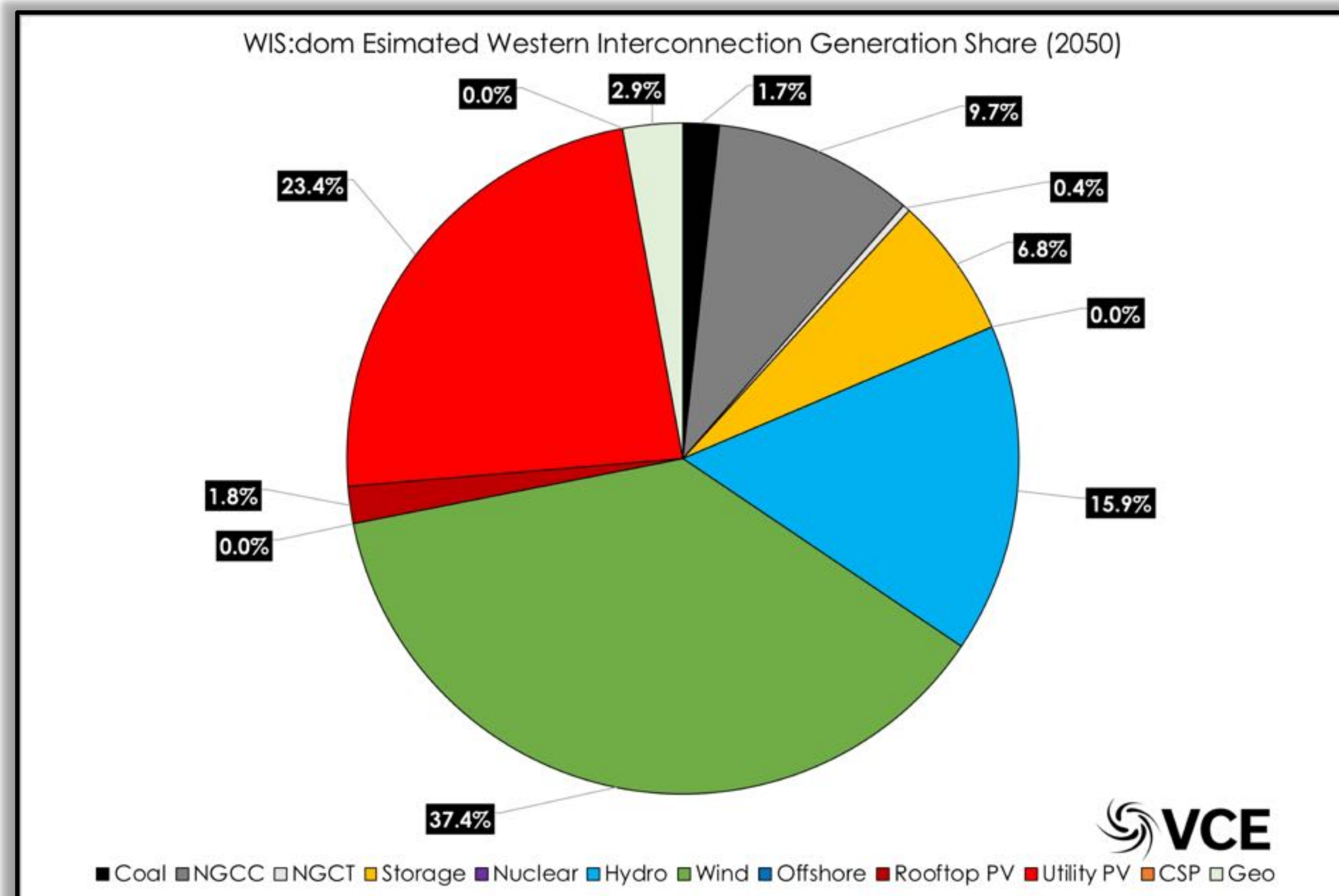
- ***Dispatchable generation is still dominant across WECC.***

WECC-wide Electricity Generation



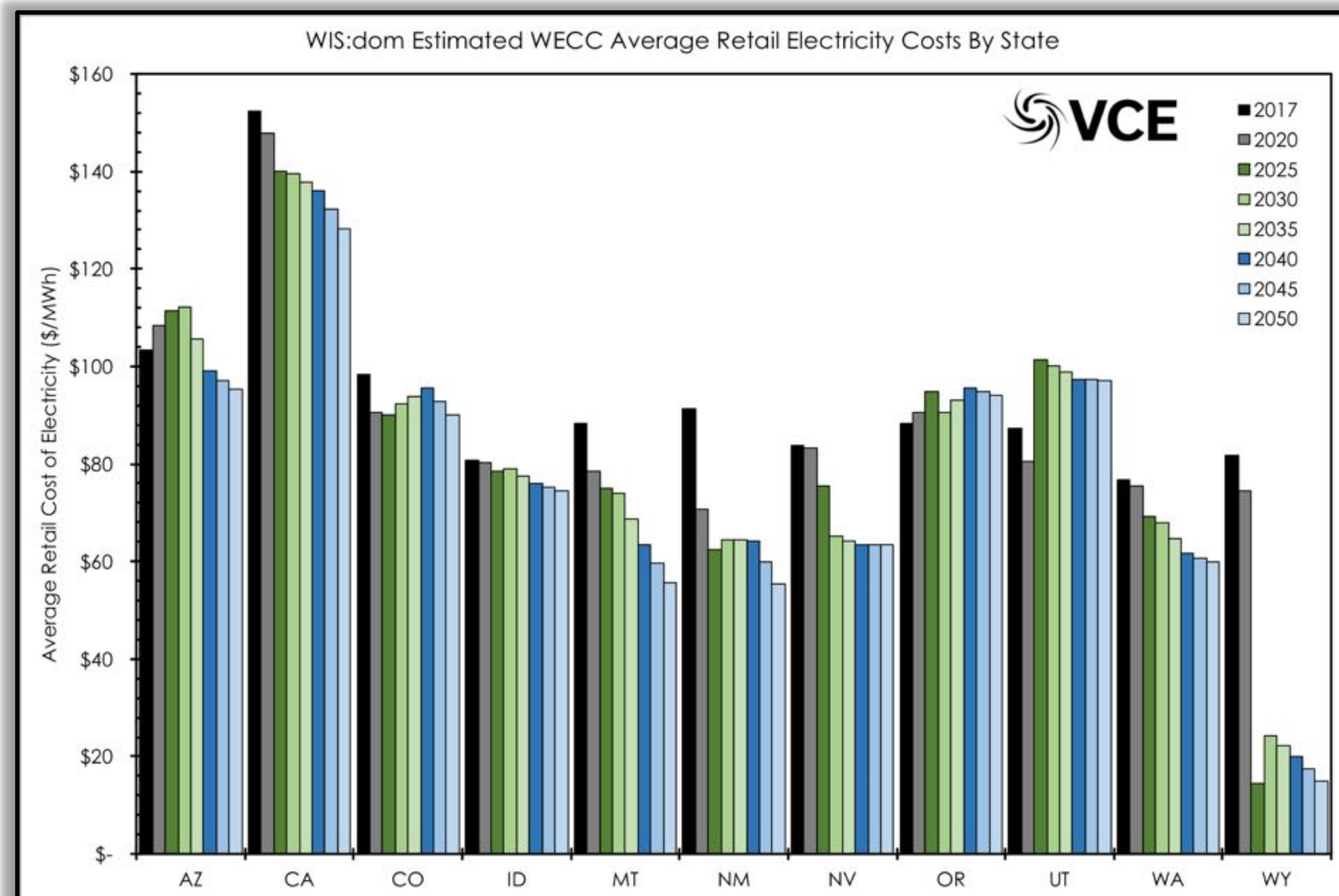
- ***Dispatchable and variable generation are approximately equal across WECC.***

WECC-wide Electricity Generation



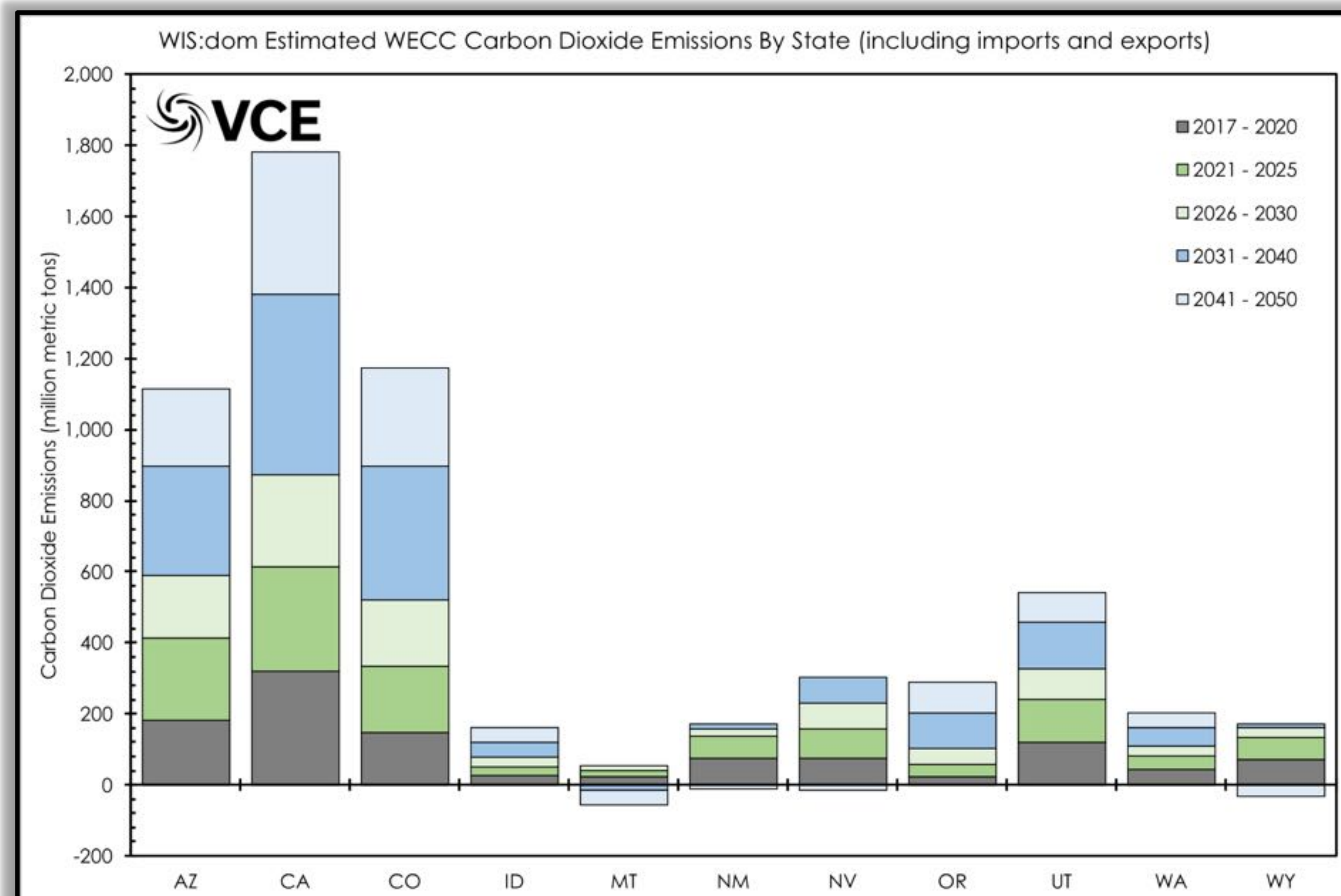
- ***Dispatchable generation share is down to 37% across WECC.***

WECC-wide Average Retail Electricity Costs



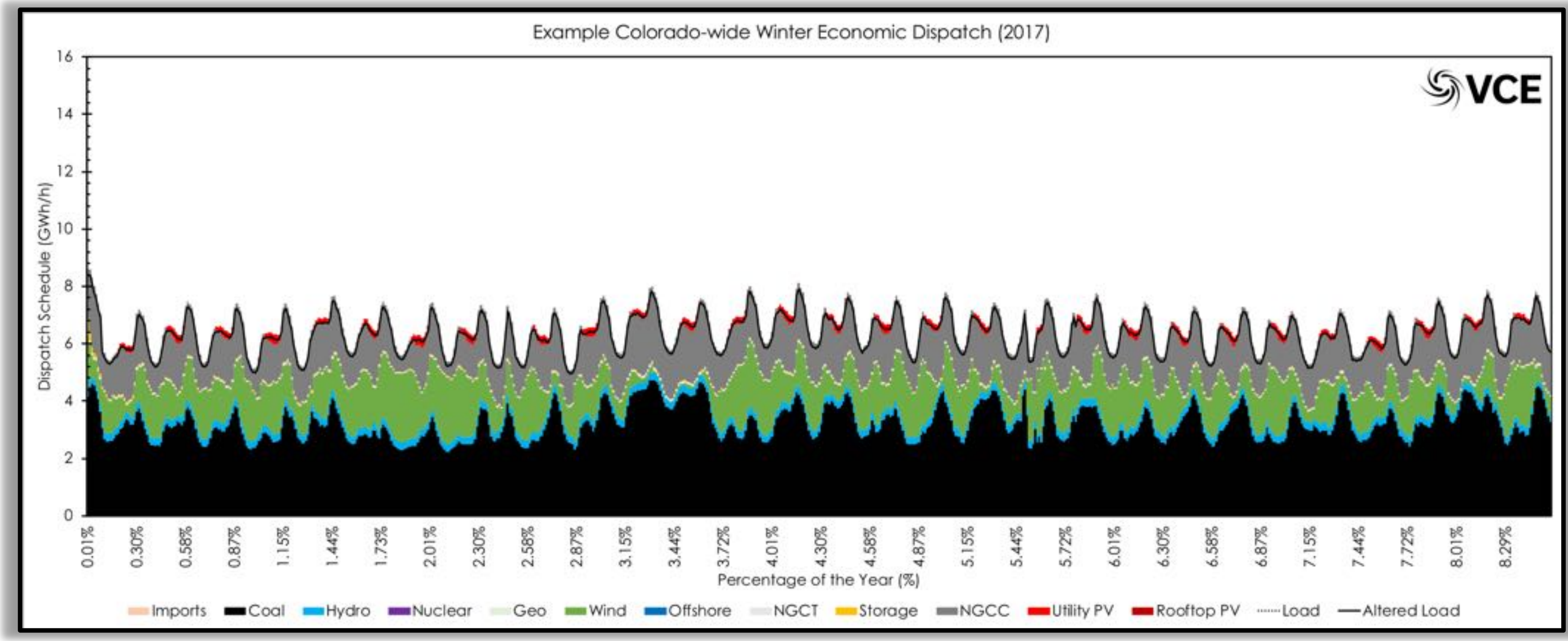
info@vibrantcleanenergy.com

WECC-wide CO_2 Emissions From Electricity



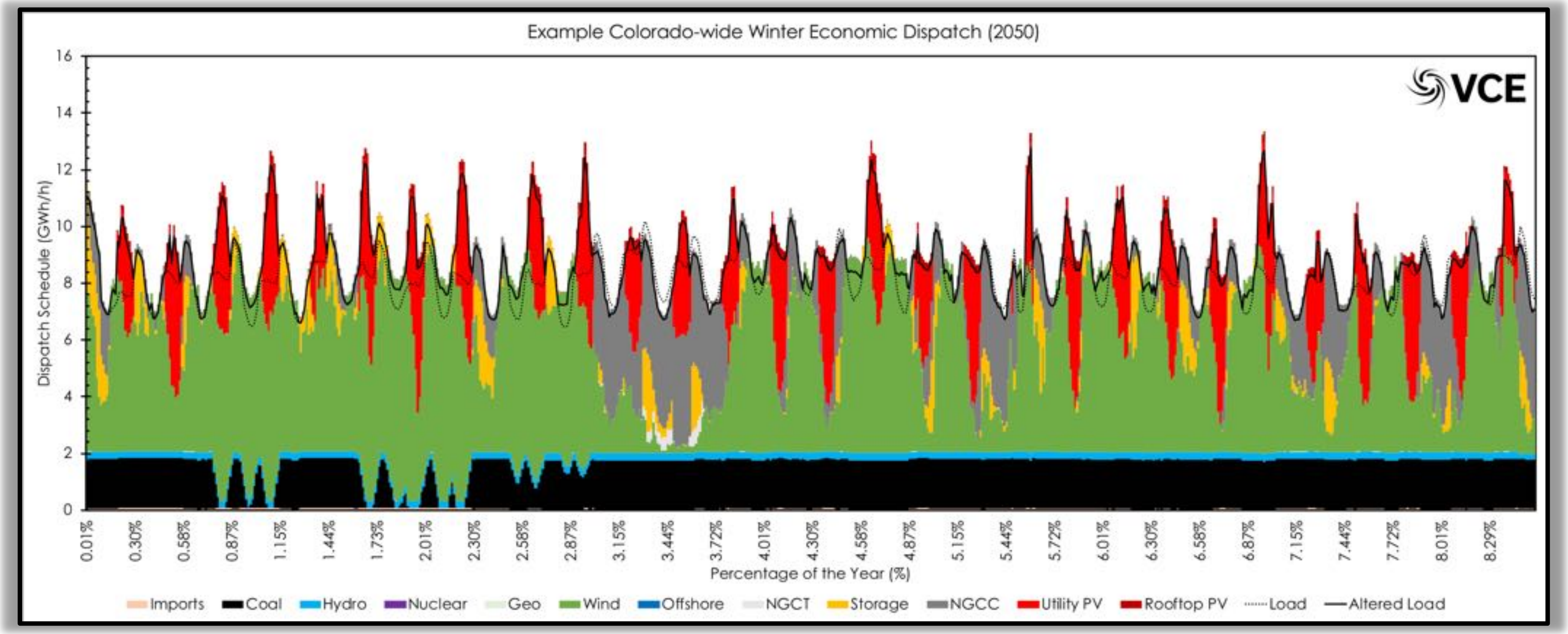
- *These emissions are traced to consumption source; so if state exports electricity the emissions are counted in recipient state.*

Colorado Winter Dispatch



info@vibrantcleanenergy.com

Colorado Winter Dispatch



info@vibrantcleanenergy.com

VIBRANT CLEAN ENERGY

Thank You

Dr Christopher T M Clack
CEO Vibrant Clean Energy, LLC

Telephone: +1-720-668-6873
E-mail: christopher@vibrantcleanenergy.com
Website: VibrantCleanEnergy.com
Twitter: @Clacky007